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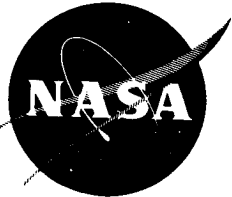
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TECHNOLOGY SURVEY

Technology
Utilization
Division

PLASMA JET TECHNOLOGY

Compiled and Edited by:

P. R. DENNIS

C. R. SMITH

Clyde Williams and Company
Columbus, Ohio

D. W. GATES

J. B. BOND

Marshall Space Flight Center
Huntsville, Alabama

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Foreword

The Administration of the National Aeronautics and Space Administration has established a technology utilization program for "the rapid dissemination of information . . . on technological developments . . . which appear to be useful for general industrial application." From a variety of sources, including NASA Research Centers and NASA contractors, space-related technology is collected and screened; and that which has potential industrial use is made generally available. Information from the nation's space program is thus made available to American industry, including the latest developments in materials, processes, products, techniques, management systems, analytical, and design procedures.

This publication is part of a series intended to provide such technical information. It emphasizes the industrial potential of plasma generators in materials testing, coating, and spraying, chemical synthesis, and other industrial operations. It includes accounts of NASA contributions to such technology and the instrumentation involved, and lists NASA plasma-arc facilities.

Clyde Williams & Company compiled the information presented in this survey.

THE DIRECTOR, *Technology Utilization Division*
National Aeronautics and Space Administration

Acknowledgments

This survey of some of the present industrial applications of plasma-arc devices and NASA work in this field was undertaken to stimulate the interest and imagination of readers concerned with technological progress. NASA work with such devices has resulted largely from the need to simulate the environments into which space vehicles are sent and from efforts to develop propulsion units for satellite attitude and position control. Equipment manufacturers have been more concerned with welding, cutting, chemical synthesis, particle preparation, melting, and other such operations, and their views are presented to indicate ways in which NASA research and development may prove helpful here on earth as well as in space.

NASA work in the plasma-arc field is summarized briefly and a bibliography with selected abstracts is included for readers who wish further information.

Both arc heater and propulsion work are noted because both are of industrial interest. Work done on small thruster units may prove valuable in cutting, welding, etc., and that done on larger units may be adaptable to chemical and other processes.

The material was collected with the help of the technology utilization officers at NASA centers and many others, some of whom contributed large sections as indicated in footnotes. M. R. Scheckner provided the illustrations and photographs.

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Introduction¹

Arcs and arc processes have been used since the turn of the century in a myriad of applications ranging from welding to chemical synthesis. However, no concerted research effort was carried out in this field until the 1950's when first the Department of the Navy and then the Army and Air Force saw fit to fund a number of research endeavors. More recently, NASA has entered the field both in its own laboratories and through contract research support, and the entire arc and plasma field has progressed remarkably since this support became available.

With the advent of the missile and space age, a need became apparent for a method of producing reentry conditions in the laboratory in order to investigate the many phenomena that missiles and spacecraft encounter as they travel back to earth. The effort to produce these conditions has led to the development of large arc heaters and plasma jets which can be controlled precisely to give the exact parameters desired. Small, compact and low power thrusters have also been developed, leading to small cutting and welding torches and high intensity light sources.

From the early beginnings of the plasma jet in Germany, through the work of Finklenburg, this area of physics has progressed to a point where it has become a separate field of investigation and has generated several new theories of arc propagation.

The application of the plasma arc to industrial processes has taken diversified paths. In the metal working industry, new and faster methods of welding and cutting have been developed using plasma jets and arcs. Cutting speeds up to five times that of the oxy-acetylene torch have been realized. One of the most useful developments that has come from the more recent research is plasma spray-coating with high-temperature-resistant materials; this was hitherto impossible. Plasma jet devices have also found application as heat sources for high-temperature controlled-atmosphere furnaces.

Studies on the use of plasma devices as radiation sources have led to the vortex-stabilized radiation source where a brightness of 5,000

¹ Prepared by Mr. Charles Stokes, Temple University.

candles per sq. millimeter and a luminous efficiency of 60 lumens per watt may be achieved.

In chemical synthesis the impact of the plasma arc device is just beginning to be felt. Because of the high temperature within the plasma stream (10,000 to 30,000° F.), chemical elements and compounds are fragmented into radicals and atoms when introduced into it. These radicals and atoms, when cooled rapidly, can and do react to produce compounds other than those initially introduced. For example, methane yields acetylene when passed through a plasma arc of helium, argon or hydrogen. Acetylene is presently manufactured by an arc process, and the plasma jet has been employed in the preparation of many refractory-metal compounds.

Research in plasma technology and devices has tremendous potential for producing new and varied industrial processes which will add to our economic growth and development. Results of these efforts are already being felt in the national economy. It has been estimated that, in addition to the benefits in defense and space, approximately \$100,000,000 has been added to the gross national product by a government expenditure of \$30,000,000.

In the last ten years, plasma technology has made great strides due mainly to the support of the Army, Navy, Air Force, and National Aeronautics and Space Administration. But some of the greatest gains are yet to come through the use of plasma-arc devices. If the level of effort increases at the present rate, the next ten years will bring new theories, methods, equipment and processes which will revolutionize this field. Industrial application of many of these research developments will undoubtedly be feasible within a few years.

Plasma Generators

HISTORY

The phenomenon of a heat source which comes into existence at the upper limit of chemical flames has intrigued research scientists since the turn of the century. Since the introduction of early arc devices, engineering researchers have continually sought better and more efficient ways of obtaining temperatures which would allow both the research scientist and industrial manager the greatest latitude in working with materials. Today several techniques are capable of producing temperatures beyond which metals and liquids as such cease to exist. Table 1-I compares a number of these sources. On a comparative basis, the plasma jet is potentially a source of controllable intense heat and, as such, warrants consideration as a commercial device for industrial use.

TABLE 1-I.—*High Temperature Heat Sources*

Heat Source	Approximate Temperature °F	Gas Velocity fps	Maximum Gas Enthalpy Btu/lb.
Open flames, air and oxygen.....	3, 000–7, 500	1–600	4,700 O ₂ 1,300 Air
Enclosed flames, air and oxygen.....	3, 000–7, 500	1–9, 000	4,700 O ₂ 1,300 Air
Open arc, low intensity.....	6, 000–8, 500	1–30	25,000 N ₂ 1,000 Air
Open arc, high intensity.....	6, 000–10, 000	1–100	30,000 N ₂ 8,000 Air
Plasma jet, arc contained within device.	5, 000–30, 000	1–30, 000	130,000 H ₂ 100,000 N ₂ 33,000 Air
Plasma jet, arc transferred to object receiving heat.	6, 000–60, 000	1–40, 000	200,000 H ₂ 30,000 N ₂
Solar and arc image furnace.....	6, 500	0	

Historically, the illuminating arcs and electric furnace arcs were the forerunners of the plasma generators of interest in this work. In Norway, starting about 1910, nitrogen fixation was accomplished on a commercial scale (at 2 to 4 percent conversion efficiency) for a number of years using arc techniques. Yet, despite the vintage of very basic knowledge, practical industrial data are only now becoming available. For the most part, the modern aspects of plasma technology must be linked closely to two important factors: economics and equipment development. Despite obvious technological advantages, various designs of plasma generating devices have only recently made sufficient gains in these areas so that broad-scale application may be realized.

THE PLASMA STATE

Because of the high quality and ready availability of information elsewhere on plasma physics, this work is concentrated on the technology and applications of the plasma jet.

There are a variety of techniques for producing plasma or near-plasma conditions. Some of these techniques do not really produce plasma in accordance with the accepted definitions, viz., that the gases generated be of an energy state which involves complete dissociation and ionization. A more accurate definition of "plasma" generators which may potentially benefit industry would include heat sources capable of producing temperatures in excess of $3,000^{\circ}$ F. which are attained without exothermic reactions within the gas itself. Plasma generators can be operated at fairly low temperatures, $3,000$ or $4,000^{\circ}$ F. at a pressure of 1 atmosphere.

Actual ionization of part of the gas takes place within the heating region, i.e., where the arc strikes or where the high frequency field couples to the gas. From an applications standpoint, however, the principal interest lies in the average properties of the gas leaving the device. Considerable mixing of the products occurs after exit from the arc-heated region and average gas temperatures are well below the ionization level of the gas. In many cases, some residual ionization may remain in the plasma as it leaves the device, but again this is more related to relaxation phenomena than to equilibrium conditions.

Figures 1.1 through 1.6 show schematically the various methods of heating to "plasma" temperatures. Several of these designs have been developed to a greater state of commercialization than others, and in the following sections they are considered individually and then compared graphically with various devices.

Basically, the following sections describe plasma generators of two designs: in the first the plasma is generated by an arc between two

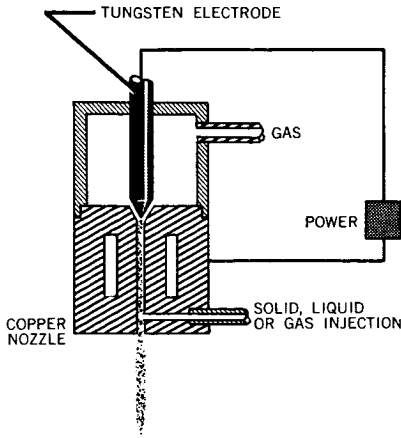


FIGURE 1.1—Direct current nontransferred torch.

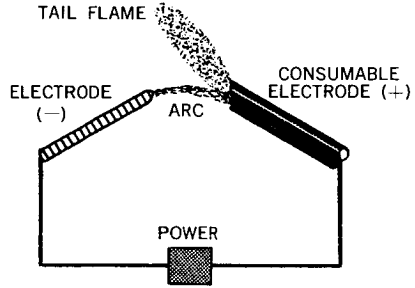


FIGURE 1.2—High intensity arc.

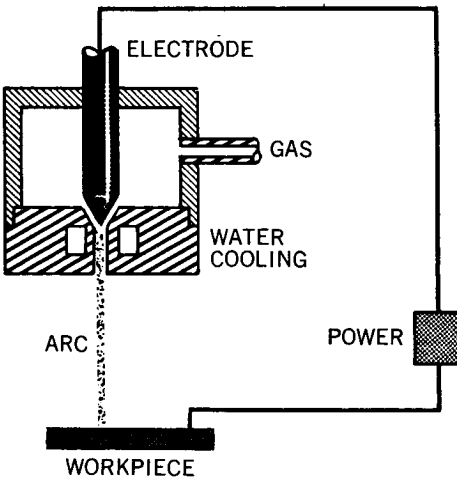


FIGURE 1.3.—Direct current transferred torch.

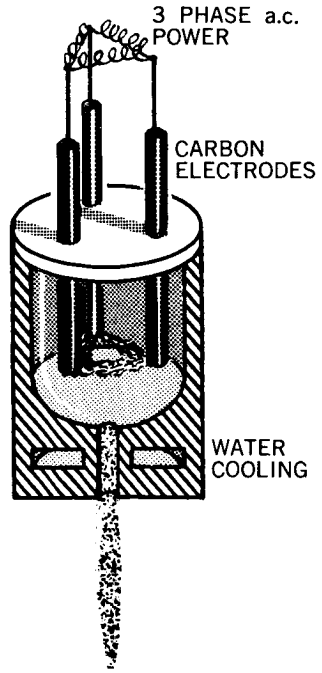


FIGURE 1.4.—Three phase 60 cycle ac torch.

electrodes; in the second the plasma is generated without the use of electrodes.

Plasma devices are variously referred to as plasma generators, plasma jets, plasma torches, plasma heaters, constricted-arc heaters, and jets. Commercial devices may also be called plasma-flame spray guns, plasma-flame cutters, or plasma-arc welders—depending on the particular use intended for the specific piece of equipment.

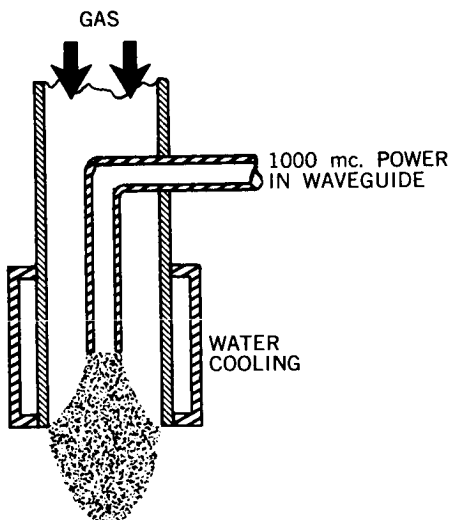


FIGURE 1.5.—Capacitance type plasma generator.

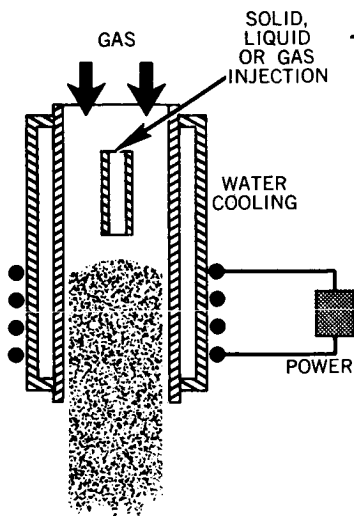


FIGURE 1.6.—Induction coupled plasma torch.

CLASSIFICATIONS OF PLASMA GENERATORS

Modern plasma generators that are maintained with an arc are of two types—nontransferred-arc and transferred-arc. The classifications refer to the positioning of the electrodes with respect to each other and to the plasma flame. Figures 1.1 and 1.3 give simplified schematic representations of the two types.

In a typical nontransferred-arc unit (Figure 1.1), the plasma gas flows through the arc struck between the anode and cathode and emerges as the hot-plasma stream or “flame” through an orifice in the anode. The flame is external to both electrodes.

In the transferred-arc type, the cathode is some distance (usually less than six inches) from the “working” anode, and the flame is between the electrodes. (A pilot anode may surround the cathode. This is for starting the arc only.) An arc is “struck” between the two electrodes by either a capacitance or high-frequency discharge with the dc arc following the ionized path thus generated. The arc is blown into the nozzle which is so sized that most of the gas blown through it must come into intimate contact with the electric arc region. Heat losses with this device result from high electrical-resistance losses at both the cathode and anode, radiative from the plasma to cooler surfaces, and convective losses to the anode wall. The cathode and anode resistance losses with most commercial devices are normally in the range of 20 percent, while the convective and radiation losses vary widely with the particular design. Some produce

losses as high as 40 percent, while others are in the range of 10 to 15 percent. Most devices are supplied with conventional selenium rectifier units with ac to dc conversion efficiencies ranging from 65 to 75 percent. In many of the larger installations, silicon units have been used. Adequate field experiments have not been made for an accurate prediction of the effect of various types of power generating systems on electrode life. In a dc system any foreign materials injected into the plasma stream must be injected downstream of the arc determination at the anode to avoid contamination of both the anode and cathode. The dc device, because of its relatively low voltage requirements, can be categorized as a portable heat source and consequently can be located some distance from the power sources. It may also operate as a hand device.

Plasma devices are also classified according to the method used to stabilize the arc. Designs fall into two general categories: gas-stabilized and liquid-stabilized. Thorpe (32) further categorizes the types that have been described in the literature as vortex-stabilized, gas-sheath-stabilized, wall-stabilized, magnetically stabilized, and water-stabilized.

Stabilization implies the maintenance of a continuous flame. This is accomplished by constriction and compression of the arc column by some means outside the arc itself—by a gas or liquid vortex or sheath, or by a magnetic field. Confinement of an arc increases the current density, the voltage gradient, and the column temperature.

The phenomenon of constriction with gases or liquids may be explained by the cooling effect of the stabilizer. Ionization is decreased in the cooler portions of the arc column, with consequent decrease in conductivity. This causes current density at the center of the column to increase because of the tendency for current to concentrate where conductivity is highest.

The Gerdien arc, which was the first plasma jet, used a water vortex for stabilization. Plasma jets squirted out both ends toward the electrodes. Although temperatures up to $50,000^{\circ}\text{K}$. could be produced by making the water vortex small to squeeze the arc, these devices are now mainly of academic interest. Rapid carbon-electrode consumption and the presence of water vapor in the jets ruled out most potential applications. The Gerdien arc made apparent the advantage of arc constriction to stabilize the flame and concentrate the power, but commercial use of plasma jets did not come about until Gage developed the constricted-arc torch.

In studying the arc properties of rare gases, Gage had observed the flames produced when arcs struck a water-cooled copper anode. By drilling a hole in the anode, he made the arc flame pass through it, and

the gas flow produced a crude plasma jet. The next step was to reduce the hole in size to form a nozzle which constricted the arc and the plasma.

VORTEX STABILIZED

In the vortex-stabilized unit the electrodes are made of tungsten, carbon, or other appropriate material and may be water-cooled. Gas is fed tangentially into the chamber between the electrodes to produce an intense vortex within the hollow electrode, which is usually the cathode. Thus, the arc is forced to travel from the solid anode out of the nozzle and then strike back to the front face on the hollow cathode. According to Thorpe, this design has been limited mostly to operation with noble gases, such as argon and helium, except in low pressures.

GAS SHEATH STABILIZED

The arc path in the gas-sheath-stabilized plasma jet is between a solid tungsten cathode and a hollow water-cooled copper anode. This design operates on both monatomic and diatomic gases and provides greater flexibility in adaption to chemical processes. The arc remains within the nozzle and is prevented from striking the wall by a gas sheath much thicker than the arc diameter. Vortex flow is not generally used, and arc positioning is accomplished through the gas-flow pattern and control of turbulence. Commercial designs range from a few millimeters to over 40 atmospheres.

WALL STABILIZED

The wall-stabilized design consists of a solid and a hollow electrode, with the geometry such that the plasma gas, instead of constricting the arc, becomes an integral part of the arc stream, filling the nozzle from wall to wall.

MAGNETICALLY STABILIZED

In the magnetically stabilized jet, the arc strikes radially from an inner to an outer electrode. Gas is blown axially through the annulus. The arc is rapidly rotated with a magnetic field, so that its position at various times resembles a spoke in a wheel. This design has permitted operation to high pressures without erosion of electrodes.

WATER STABILIZED

In the water-stabilized unit, both electrodes are consumable, and the solid electrode is fed either manually or automatically to keep arc length constant. Water is swirled in and taken out the back end in some designs. In others, the water and gas both leave the nozzle. Water-stabilized units have severe limitations as mentioned earlier and are seldom used.

HIGH INTENSITY ARC

The high intensity arc shown schematically in Figure 1.2 should also be mentioned because of its similarity to a plasma jet. This type of arc transfers most of the input energy to the anode face. The anode is constructed of the material to be vaporized, such as silicate intermingled with adequate pitch and carbon, which allows fabrication of an integral conductive electrode. Anode material is heated above $7,000^{\circ}\text{C}$., rapidly vaporized, and comes from the arc as a stream of vapor plasma called the "tail flame." While most plasma jets get compression of the arc column from some external source, the high intensity arc obtains its constriction by increasing the power input.

In any dc arc system the anode receives more heating due to electron bombardment. With a given set of electrodes, as the current is increased, a point is reached where normal conduction, convection, and radiation losses from the anode are not great enough to dissipate the heat generated. When such a situation exists a third transfer mechanism occurs—vaporization of the anode at a rate which is a function of the power input. In operation the anode is advanced at a rate which makes up for vaporization and thereby keeps the arc length constant. Under these circumstances the utilization of all energy is as efficient as in the transferred dc arc mode discussed later.

Potential applications include chemical synthesis, ore reduction, and areas involving processes that are amenable to the material being fabricated into electrodes and passed through the environment of the tail flame. Such a device is not applicable to welding, cutting of metals, or the production of a flame which in turn is used for other applications.

TRANSFERRED ARC

A modification of the dc plasma generator is the transferred arc device (Figure 1.3). In this unit an electric arc is struck, as in the nontransferred device, from a solid tungsten electrode. It differs from the nontransferred device in that the arc is struck through a hollow nozzle to an external conducting member. The external member is usually the object to be heated, and the device thus acts much like a melting or welding arc. Part of the arc stream is surrounded by a water-cooled nozzle.

In the low gas-flow mode of operation, the arc stream passes from the electrode to the wall with the attendant gas stream traveling at very low velocities (20 to 100 ft./sec.). When gas flow is increased and/or the nozzle is constricted to approach the diameter of the arc, the gas velocity rises. Velocities in excess of 10,000 ft./sec. are possible since the velocity through an orifice, with a given pressure drop across it, is a function of gas temperature. As the gas temperature

risers, the velocity rises. For example, a two-to-one pressure drop from the interior of the chamber across an orifice gives a velocity near 1,000 ft./sec. with nitrogen at 70° F. Gas at 3,300° F. has a velocity near 3,000 ft./sec., and a temperature of 6,000° F. will result in a velocity near 5,000 ft./sec. This transferred-arc device is primarily used in melting, welding, coating (low velocity), and cutting (high velocity) conductive materials. Speculation on other uses of the device can be made in the case where the arc is terminated at the external protected (shielded) anode. With this design, materials could be passed through the arc stream itself with resulting higher heating efficiencies and higher material flow-rates per kilowatt of input power.

AC ARC DEVICES

Thus far, only dc plasma generator designs have been discussed. An inherent advantage of ac plasma generators is the lower cost of power and capital equipment, especially in the high-power regime. One configuration is shown in Figure 1.4. Several people, both in this country and abroad, have investigated ac plasma generators and all have reached the conclusion that ac performance, as far as enthalpy and efficiency are concerned, is markedly inferior to that obtained with dc generators. Maximum reported enthalpy with air for an ac unit is about 3,500 Btu/lb. This is not believed to be inherent in the choice of ac power but is rather a reflection of the designs.

Some development effort has been directed toward using alternating current rather than direct current for powering plasma generators for use in wind-tunnels. Considerable research and money have been directed toward development of large 3-phase arc heaters for air. To date, success has been limited in that only low temperatures at low efficiencies have been produced (5,000° F. at 10 to 20 percent). Such basic limitations become obvious when one thinks of single-phase operation in a design similar to a dc counterpart. Principally, these limitations center around the fact that high-power, single-phase units greatly disturb power distribution systems. With the present state-of-the-art the alternating current plasma generators are technically interesting but are not yet commercially feasible.

HIGH FREQUENCY ARC

In the high-frequency plasma generation field, the design nearest the dc type is the capacitance device. This is shown schematically in Figure 1.5 and involves high-frequency (1,000 MC) power fed through wave guides to the plasma head. Here a capacitance-type discharge occurs between a solid central electrode and a surrounding coaxial tube. The plasma produces electronic-type excitations in the gas and is only suitable for heating diatomic gases. One of the

largest drawbacks of this device is the wave-guide power transmission to the head. A tremendous electric field is generated which disrupts communication systems unless the entire area surrounding the heat source is carefully shielded. There are also problems associated with the reliable generation and handling of ultra-high frequencies, as well as with personal safety. At the present time, it appears that application of this kind of device is limited to areas such as chemical synthesis where the peculiar type of electronic excitation may yield new species.

The induction-type plasma generator (30 MC and below) is also shown schematically, in Figure 1.6. In this device a high-frequency induction coil, as used in conventional induction heating of metals, surrounds an insulated refractory tube through which the plasma forming gas is blown. Once the gas is made conductive by sparking or other means, the resistivity is similar to that of a steel bar. Coupling can be accomplished directly to the gas in this manner, with approximately 30 to 40 percent of the ac energy which enters the device appearing in the gas stream. This device produces no radiation problems which cause interference with communication systems and can be operated with FCC approval without shielding of the work area. Commercial industrially proved power supplies are available in the frequency range up to 50 kilowatts. Because no electrodes are needed and all parts of the torch run cool, the device can be operated on any gas including air and oxygen. There are no hot electrodes to be consumed. On the other hand, some characteristics which are less advantageous are high voltages and frequencies with inherent loss when the power is transmitted long distances. Because of this loss and the hazards involved in handling these voltages and frequencies, the device cannot be classified as a hand-held movable unit but rather as a fixed installation to which the product or work must be moved. The device does not appear to have the upper temperature limitations of the dc devices. Thus it appears that it can ultimately create higher temperatures. The state-of-the-art, however, has not advanced to the point where this has been demonstrated with all gases. On the other hand, the extremely low-velocity, large-diameter plasmas produced in the induction torch operate in a mode suitable for some applications, such as chemical synthesis and other fixed torch installations.

ELECTRODE MATERIALS

Three basic materials are commonly employed as electrodes in plasma generators. These are tungsten, copper, and graphite. Tungsten may be employed with a variety of additives, such as thorium or zirconia, to improve the emission of electrons. For common applications, such

as gas heaters, tungsten is used only as a cathode. Tungsten is compatible with all inert and reducing gases but suffers severe erosion in the presence of an oxidizing atmosphere. The major reason for employing tungsten as an arc cathode is its thermionic emission capabilities. The heat loss to a tungsten cathode is generally five percent or less of the total heat loss in an arc system. The boiling of electrons in the thermionic emission process acts to remove energy from the cathode and hence to cool it. Tungsten is rarely used as an anode material since the removal of the thermionic cooling and the low thermal conductivity of tungsten make it undesirable.

When a tungsten cathode is employed, the anode material most commonly used is copper. The high thermal conductivity of copper permits it to operate with a relatively cold wall when water cooled. It is used in all atmospheres and, in general, erosion of a copper anode is very slight. Copper is also used as a cathode material in some generator designs. With proper design, copper cathodes have been successfully operated in an oxidizing atmosphere with fairly low contamination of the stream. A very intricate cooling scheme is necessary in copper cathodes to keep them from ablating, and they operate much less efficiently than tungsten because of the lack of thermionic emission. The heat loss to the cathode can exceed the anode loss when copper cathodes are employed since a large amount of energy must be added to the cathode to get electron release, and a large portion of this energy must be removed in the cooling water in order to keep the copper from melting.

When copper is used as an electrode material, some mechanism must be provided to rotate the arc foot point on the surface of the electrode to prevent local overheating and melting. As the current is increased, this requirement becomes stringent. For very low currents, wall stabilization or the development of a cold gas sheath along the electrode surface is sufficient to protect the copper anode if the magnetic fields from the current leads do not produce an asymmetrical field in the arc area. Thus, the anode foot point is free to move and actually does so as soon as a high-resistance molten spot is formed. A better method of assuring arc rotation on a copper anode is the use of swirl or vortex motion in the arc gas. Thus, the anode tries to follow the ionized gas which is swept in a helical pattern by the vortex motion, and the arc is moved around the anode surface by this motion.

When high currents are employed or when copper is used as the cathode material as well as the anode material, it is necessary to rotate the arc attachment points rapidly by means of a magnetic field in order to preserve the electrodes from severe erosion. The magnetic field may be produced by an external means, such as a solenoid coil, or the

electrodes may be so designed as to take advantage of the magnetic field produced by the current-carrying electrodes.

The other major material used in electrodes is carbon in the form of graphite. Graphite has advantages in that no cooling is necessary and magnetic fields need not be used. Its major disadvantages are the contamination of the stream which results from its use and the short operating times available without an electrode-feed mechanism. Some devices have been made which reduce the contamination level by exhausting a portion of the gas around the graphite electrodes to remove the ablated material, and by then using the center portion of the arc stream for the plasma. These devices suffer from low efficiencies but do operate on oxidizing gases with a measure of success.

Other electrode materials such as the conducting carbides have been used in laboratories but have met with little success in commercial applications.

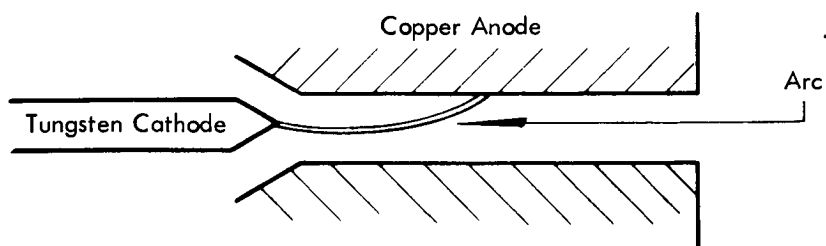
ELECTRODE CONFIGURATIONS

Almost as many electrode configurations are being used as there are companies making plasma generators. For the purposes of this discussion, a few of the more prominent dc configurations will be analyzed.

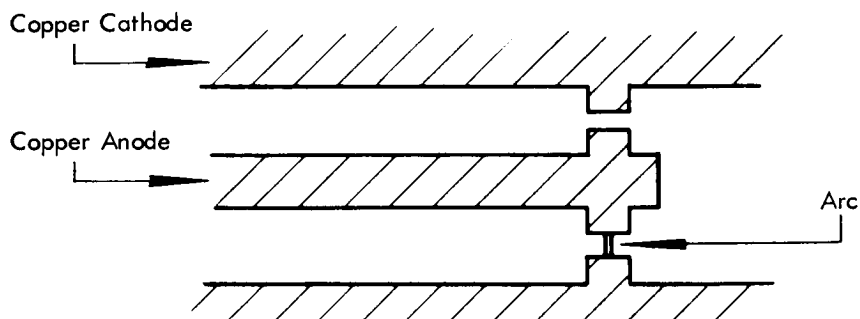
The most common configuration employs one stick electrode and one annular or cylindrical electrode (shown in Figure 1.7A). The gas enters around the stick and exhausts through the hollow electrode after passing through the arc. The cylindrical electrode can act to constrict the arc by forcing it to a smaller diameter than would occur in a free space. In some cases an insulating constrictor is used which forces the arc to maintain a smaller diameter before reaching the annular electrode.

The polarity of these two electrodes varies with the electrode material used. If tungsten is used, the stick is the cathode and the cylinder (generally made of copper) is the anode. When graphite is employed, the stick is generally the anode and the cylinder is the cathode. The same polarity is used with copper electrodes, although copper sticks of this type are very rare. The polarity of the stick is determined by which electrode must dissipate the lesser amount of heat. (The tungsten cathode and graphite or copper anode require less cooling.)

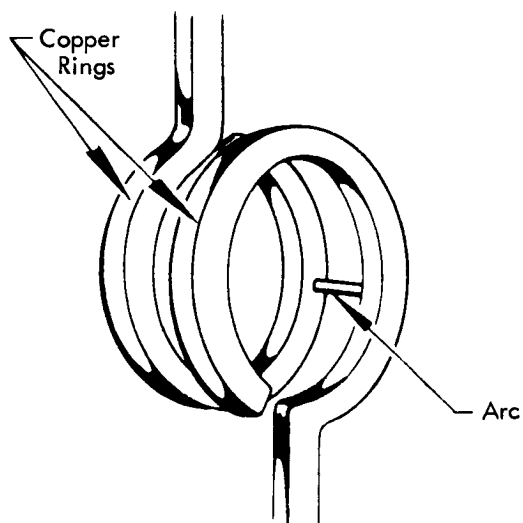
Two other configurations are employed. These are the concentric and parallel rings. Looking at the concentric rings, we have the so-called "solenoid" arc as in Figure 1.7B. This uses a copper stick (anode) where the arc is struck on the circumference of the stick rather than on the end. The annular electrode (cathode) is positioned



A - STICK AND CYLINDER CONFIGURATION



B - "SOLENOID" CONFIGURATION



C - PARALLEL RING CONFIGURATION

FIGURE 1.7.—Dc electrode configurations.

Courtesy of Plasmadyne Corporation

around the stick rather than ahead of it and the arc is struck across the gap between the circumference of the stick and the container. The arc is rapidly rotated over both electrodes by means of an external magnetic field. There are other variations on this, but most are similar in operation.

The parallel ring configuration can be seen by examining one case. Two identical copper rings are placed a distance apart with the leads to the rings diametrically opposite each other as schematically shown in Figure 1.7C. The arc is struck between the rings and is rotated rapidly by the self-induced magnetic fields of the electrodes. These rings are water-cooled and may be circular or rectangular in shape. A variation of this configuration employs two cylindrical copper electrodes separated by an insulated restrictor. In this latter case, an external magnetic field is necessary for arc rotation.

There are advantages and disadvantages to each of these configurations. The stick-and-cylinder configuration has the advantage of causing a large percentage of the gas to flow through the arc because the gas and arc must simultaneously pass through the constricted section. This design with a tungsten cathode also rejects the least amount of heat to the cathode and thus operates most efficiently. The stream contamination is also less with a tungsten cathode than with the other materials. It has the disadvantage that it can only be used with a reducing or inert gas in the area of the cathode. Presently, development work is being carried out to overcome this disadvantage.

The parallel and concentric-ring electrodes have the disadvantage that only a small percentage of the gas is actually heated directly by the arc since the arc covers only a small portion of the gas-flow area. These devices are capable of operation in an oxidizing atmosphere if the contamination level can be above one percent of the gas flow. The life of the electrodes is much shorter with this design and the energy losses to the electrodes are larger than with the stick and cylinder.

The performance of a plasma generator is directly related to the portion of the gas which actually flows through the arc. Thus, two electrodes operating in a large chamber can operate efficiently but only at low enthalpy since only a small percentage of the gas is heated by the arc. In order to obtain high enthalpy, it is necessary to pass as much gas as possible through the arc directly. Only the stick-and-cylinder configuration has produced enthalpies with air or simulated air above 10,000 Btu/lb.

CALIBRATION AND OPERATING EFFICIENCY

The detailed calibration of a high-temperature supersonic jet is in itself a formidable task, primarily because of the complications ensuing from possible deviations from chemical and thermal equilibrium

within the gas as shown in Figure 1.8. It is essential that a fairly extensive calibration accompany an arc-plasma-generator development program in order to be assured that the required high enthalpies are realized in the flow. Fortunately, advanced instrumentation is now in existence to permit the direct measurement of important gas properties. (See Chapter 5 on "NASA Developed Instrumentation for Measurements in Partly Ionized Gases" for examples of work in this field.)

It is important to clarify the nomenclature presently being used to describe the operating power levels of arc heaters. Unfortunately the kilowatt level usually refers to the energy input to the torch, while the total heat input to the gas is a function of the efficiency. Thus, some 5 and 10 Mw. systems have been built, generally using alternating current, but their efficiency is between 7 and 10 percent. It is important to note that the average efficiency of a 1-megawatt dc torch is between 40 and 60 percent. It would be worthwhile for the industry to consider some standard form for defining plasma devices. One suggestion is a simple terminology such as "5/10" in which the first figure would represent the average of maximum power to the gas, while the second figure would denote the torch capability. The decimal equivalent would then represent the average or maximum efficiency.

Figure 1.9 is a curve of obtainable enthalpy limits in 1962. Figure 1.10 shows an 80-kw. torch with a 200-kw. nozzle attachment. Figure 1.11 shows a sample mounted in a supersonic gas stream.

Atmospheric pressure electrodes are available for operation on nitrogen, simulated air, straight air, argon, and helium. Operation on nitrogen might be termed the "standard" mode of operation, and the simulated air operation (with oxygen being introduced in the arc chamber upstream of the anode terminus) is very similar. For high-pressure operation, configurations are available for operation on nitrogen, on nitrogen with oxygen mixing in the arc chamber, and on straight air.

Electrodes of the unchoked "atmospheric-pressure" type have been operated at from 1/10 to 3 atmospheres chamber pressure. The high-pressure set of electrodes is capable of operating from 2 to 50 atmospheres, for limited duration runs. For high-pressure operation the maximum enthalpy ranges from the values at 1 atmosphere to 4,000 Btu/lb. at 30 atmospheres. For argon operation, the enthalpy range is from 2,000 to 10,000 Btu/lb.

Torch operating-power efficiency is approximately 50 percent with argon or helium operation, 55 to 60 percent for high-pressure nitrogen and simulated air operation, 60 to 70 percent for atmospheric nitrogen

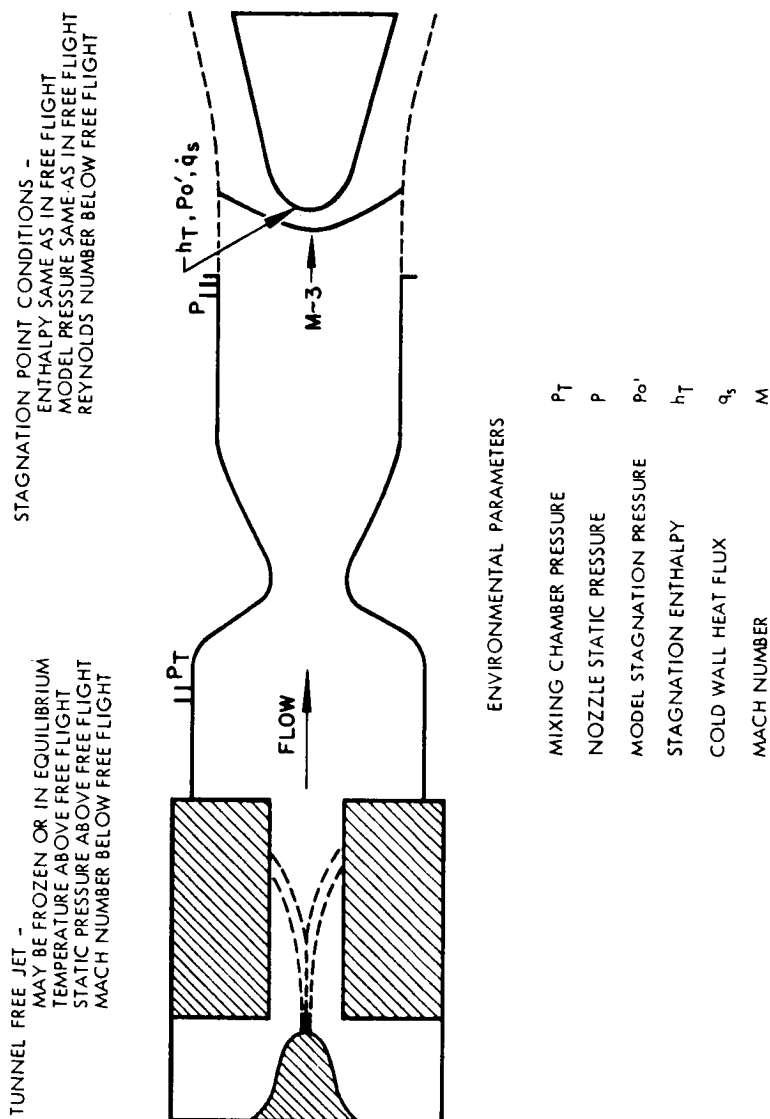


FIGURE 1.8.—Simulation.

Courtesy of Plasmadyne Corporation

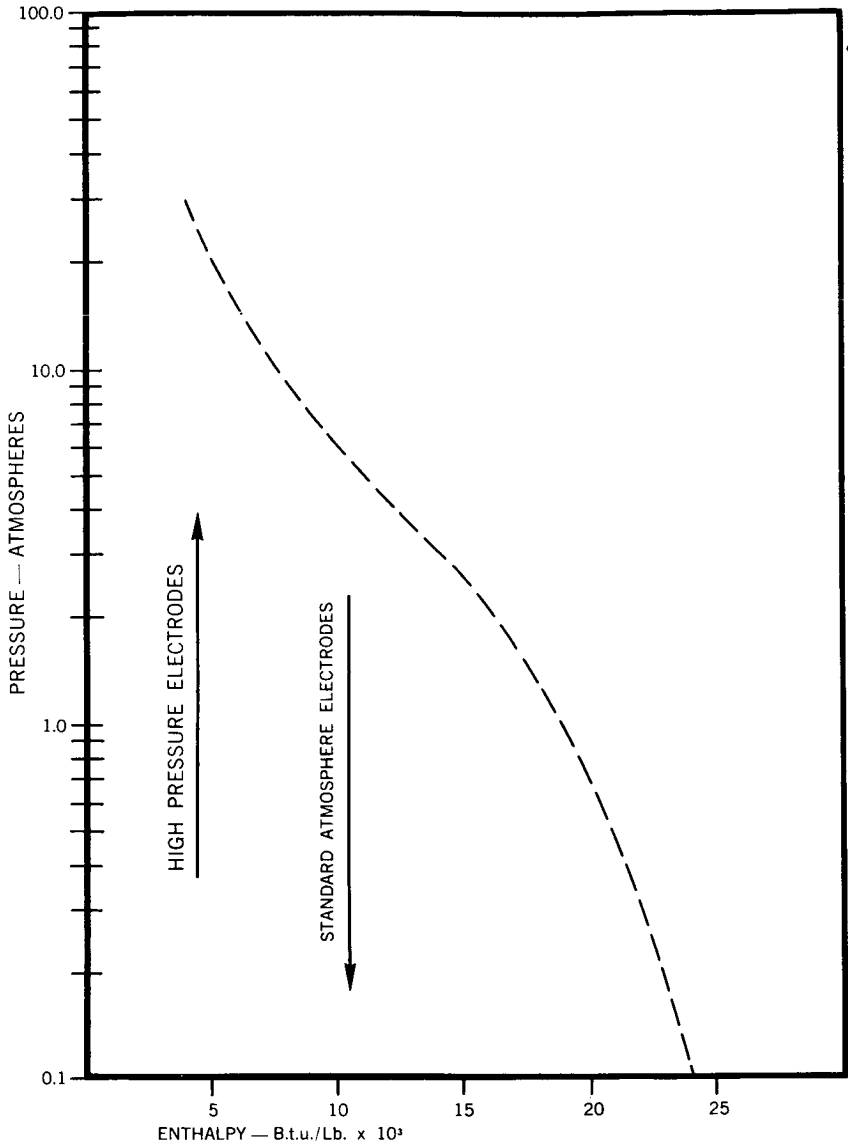


FIGURE 1.9.—Performance curve.

Courtesy of Thermal Dynamics Corporation

operation, and up to approximately 80 percent for nitrogen operation at 1/10 atmosphere.

The mass flow obtainable for a particular operating point is easily calculated by multiplying the operating power level by the anticipated efficiency to obtain a figure of kilowatts to the gas, which is very nearly

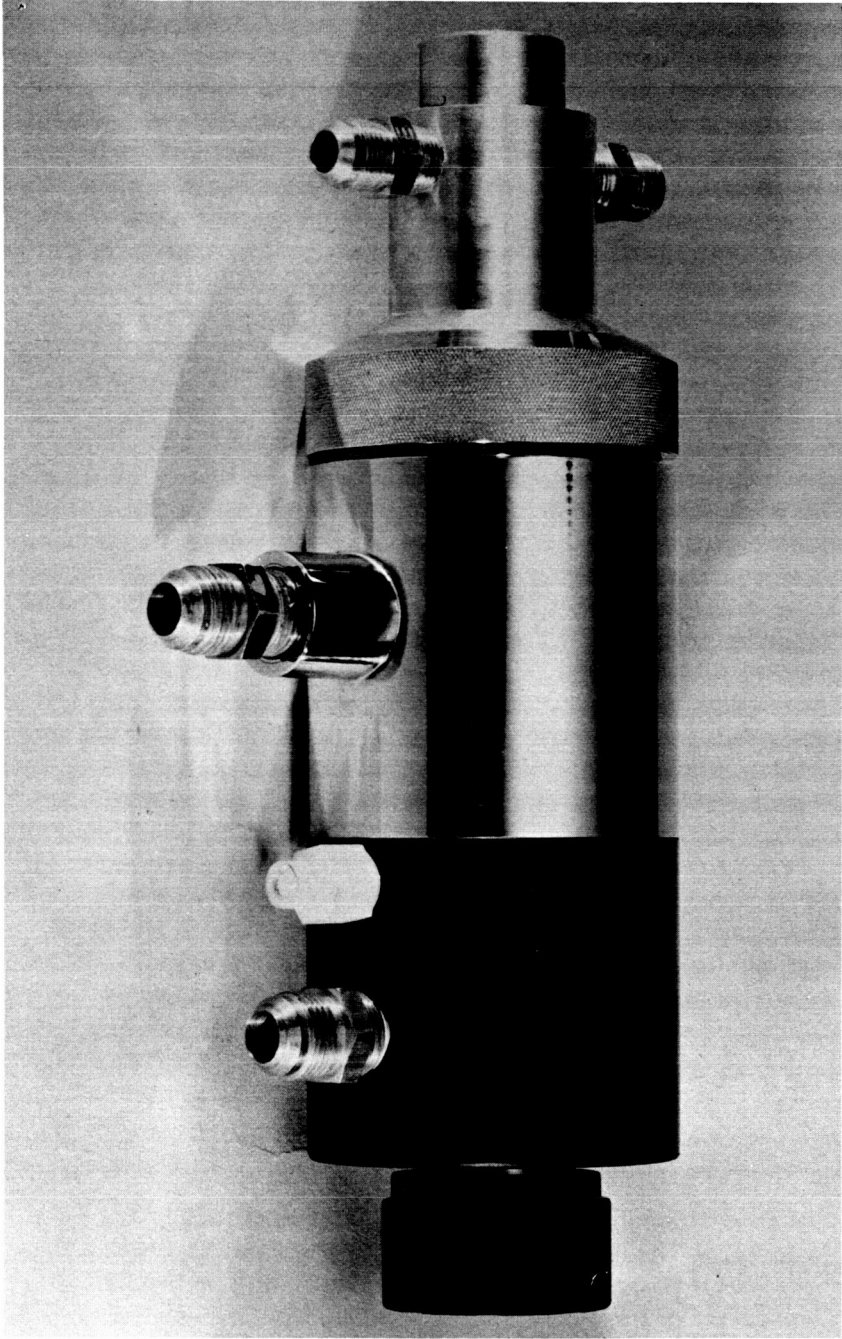


FIGURE 1.10.—80 kw. torch with 200 kw. nozzle attachment.

Courtesy of Thermal Dynamics Corporation

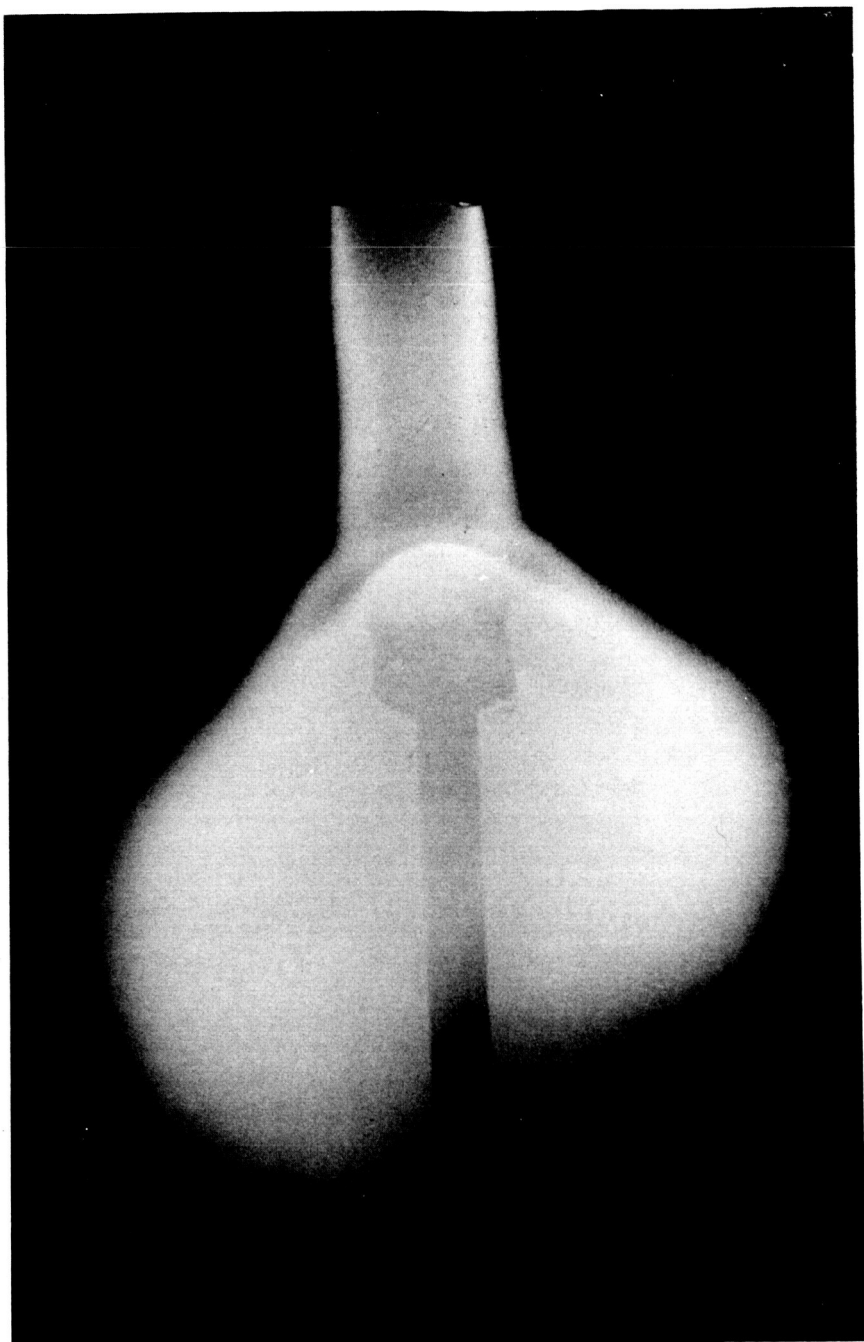


FIGURE 1.11.—Sample mounted in supersonic gas stream.

Courtesy of Thermal Dynamics Corporation

equivalent to Btu/sec. This figure can be divided by the enthalpy at which it is desirable to operate to obtain the torch gas flow in pounds per second. Typical nitrogen operation with atmospheric nozzles is from 0.04 to 0.1 pound per second flow. For the high-pressure electrode assembly, the figure would be from 0.1 to 0.5 pound per second. As an indication of the versatility of the equipment, however, the high-pressure assembly has been operated at a flow rate of 0.0005 pound per second at 220-kw., and at 1 pound per second at $1\frac{1}{2}$ megawatts. Refer to Table 1-II.

TABLE 1-II.—*Examples of Mass Flow Relations*
Courtesy of Thermal Dynamics Corp.

Net Power in gas (MW)	Pressure (Atm)	Enthalpy (Btu./lb.)	Efficiency Percent	Gross Power to Heater (MW)	Voltage ^c (V)	Current Amperes	Number of Floating Sections	Max. Arc Length (Ft.)	Gas Mass Flow (Lb./sec.)
5	5	3,000	65	7.7	1,500	5,000	1	4	1.58
5	5	6,000	50	10	2,000	5,000	2	5	.79
5	5	9,000	40	12.5	2,500	5,000	3	6	.53
5	100	2,000	40	12.5	6,250	2,000	1	3	2.38
5	100	4,000	33	15	7,500	2,000	1½	3½	1.19
5	100	6,000	25	20	10,000	2,000	2	4	.79
20	5	3,000	65	31	6,200	5,000	6	9	6.32
20	5	6,000	50	40	8,000	5,000	8	11	3.16
20	5	9,000	40	50	10,000	5,000	10	13	2.11
20	100	2,000	40	50	25,000	2,000	7	10	9.50
20	100	4,000	33	60	30,000	2,000	9	12	4.75
20	100	6,000	25	80	40,000	2,000	12 +	14	3.16

Applications of Plasma-Arc Technology

MATERIALS TESTING

Since the dc plasma-arc torch is capable of generating continuous temperatures and heat fluxes which are a factor greater than those for any other known device, the first natural outlet was in materials testing and aerodynamic studies. Initially, all units operated in the 40- to 50-kilowatt power range with enthalpies (at atmospheric pressure) between 12,000 and 16,000 Btu/lb. of nitrogen. Second-stage mixing nozzles were employed for secondary oxygen injection to produce simulated air at enthalpies between 8,000 and 12,000 Btu/lb.

As the demands for the larger test sections increased, the next operating range was 100 kw., then 200 kw., then 300 kw. Presently this power level is being phased out, and the leaders in the field rarely consider units below one megawatt (1,000 kw.). Not only has the power level risen rapidly, but the need for higher arc plenum-chamber pressures to simulate reentry environments has placed heavy demands on equipment manufacturers. Several Government organizations were contemplating the installation of 5- to 10-megawatt facilities in 1964. A 5-megawatt unit was in operation at ARGMA (Army Rocket and Guided Missile Agency). A 50-megawatt unit was under construction and NASA had requested feasibility studies for a 200-megawatt system.

HYPERTHERMAL REENTRY SIMULATION¹

The urgent need in recent years for high-temperature materials test data has prompted the use of various high-temperature testing facilities, including arc-heated hyperthermal tunnels. These needs primarily resulted from the progressively increasing requirements of space-flight vehicles. It is well to review briefly what some of the first hyperthermal simulation requirements were, how these requirements have increased, and how arc technology has progressed to meet new demands.

¹ Prepared by Shirley L. Grindle, Manager, Material Test and Evaluation Group, Plasmadyne Corporation.

Initially, plasma-arc facilities were designed to produce the high heat-transfer rates required for testing ICBM nose cones. This heating takes place at moderate enthalpies of about 10,000 Btu/lb. Because of the short time durations associated with ICBM reentry, it was not necessary that the tunnel be able to operate continuously for more than a few seconds. Indeed, a tunnel was considered "continuous" when the arc generator and nozzle would out-last the model tested.

Recently there has been increasing interest in vehicles which reenter at speeds in excess of the ICBM velocities, particularly vehicles returning from a lunar orbit. These vehicles have, in general, a lower peak heating rate (associated with deceleration at higher altitudes) although the stagnation enthalpy is higher, corresponding to the higher flight velocity. Further, the reentry times are, in general, much longer, being in the order of hours for some proposed radiation-cooled manned vehicles. Some of the important vehicles and characteristic flight speeds and enthalpies are listed below:

Vehicle Class	Flight Speed	Stagnation Enthalpy
ICBM.....	23,000 ft./sec.....	10,500 Btu/lb.
Satellite.....	25,000 ft./sec.....	12,500 Btu/lb.
Lunar Probe.....	35,000 ft./sec.....	25,000 Btu/lb.
Mars Probe.....	45,000 ft./sec.....	40,000 Btu/lb.

Prior to 1960, most arc tunnels were limited to about 15,000 Btu/lb. in enthalpy, and to continuous run times of not more than five minutes. However, with improved water-cooled electrodes, there was some evidence that small conventional arc generators (100 kw.) could produce high-enthalpy flows of the order of 20,000 Btu/lb. with relatively low contamination. On the basis of this work, it appeared that the attainment of parabolic reentry enthalpies (25,000 Btu/lb.) associated with lunar probes was feasible using larger arc generator units of 500 to 1,000 kw. to accommodate model sizes of three to six inches in diameter.

Achieving the proper enthalpy alone is, of course, not sufficient for meaningful flight simulations. A high velocity (supersonic) flow field also must be produced of sufficient Mach number that a typical hypersonic pressure- and heat-transfer distribution is produced over the test model. In addition, the flow must be steady, uniform, free from contamination (electrode material, etc.), and well calibrated.

The heart of any hyperthermal reentry simulation facility is the plasma generator system used to provide heating of the gas flow. A

typical plasma generator and nozzle system used at Plasmadyne Corporation is shown in Figure 2.1. This generator utilizes a tungsten cathode and copper anode, both of which are water cooled. Nitrogen is introduced into the arc chamber tangentially to produce a strong gas vortex for arc stabilization. Oxygen, to produce simulated air, is introduced downstream of the tungsten cathode, but upstream of the anode foot point. The hot gases are then expanded in a mixing chamber. This greatly reduces cross-sectional variations in the flow. The gases subsequently pass through a convergent-divergent supersonic nozzle and onto the test model.

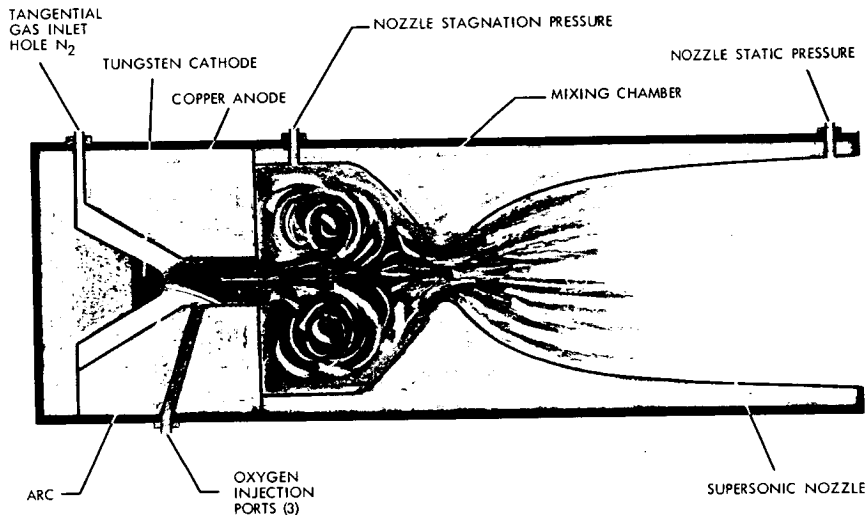


FIGURE 2.1.—Typical plasma generator and nozzle system.

Courtesy of Plasmadyne Corporation

Because of their ability to produce supersonic gas streams having an enthalpy level comparable to that anticipated in free flight, plasma generators have found wide application in simulating various reentry conditions. The plasma generator is typically mounted in a test chamber which may be evacuated to simulate the ambient pressure associated with the reentry altitude. Various probes are utilized to define accurately the environmental parameters including enthalpy, heat-transfer rate, and model stagnation pressure. Other instrumentation is provided to monitor model performance during the course of a test. A typical test chamber is shown in Figure 2.2.

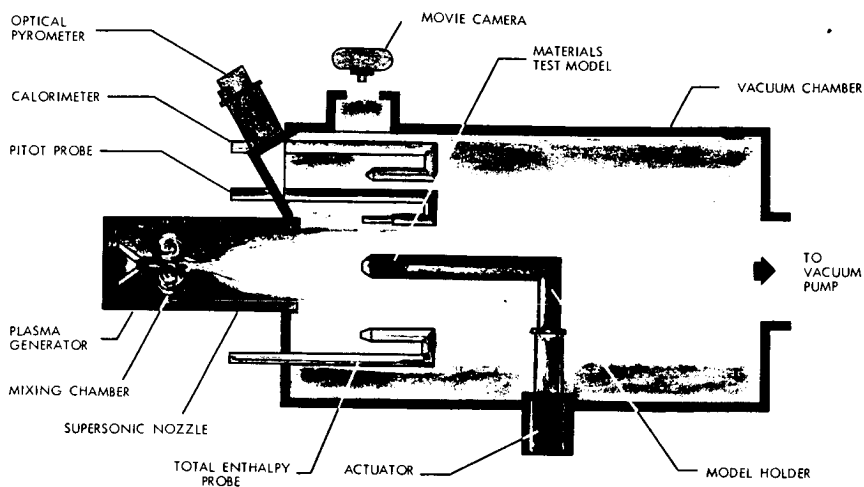


FIGURE 2.2.—Test chamber.

Courtesy of Plasmadyne Corporation

In reentry simulation testing, parameters such as enthalpy and stagnation pressure may be comparable to those experienced in free flight, although the Reynolds number is lower. The simulation of these conditions is predicted upon the formation of a bow shock wave, however, and this requires a model of somewhat smaller dimension than the gas stream. If the model is larger than the stream, a bow shock wave will not form and the simulation achieved is far from realistic and of little or no value. This is of particular significance, since nearly all investigators desire to test full-scale, or nearly full-scale models. Many have used a splash-type test in which a large model is inserted into a smaller gas stream and the hot gas is allowed to splash over the model. The results of such a test are of doubtful value except for comparing the performance of different materials under comparable but poorly defined test conditions.

Many organizations have some form of hyperthermal reentry simulation facility available. It would not be appropriate to the discussion herein to cite all of these, but there have been several facility compilations made in recent years. In order to demonstrate the type of reentry conditions which can be simulated, however, the operating characteristics of three arc facilities are tabulated below and shown in Figure 2.3.

	Moderate Enthalpy	High Enthalpy	High Pressure
Enthalpy Range (Btu./lb.).	500 to 19,000-----	500 to 25,000---	500 to 3,500.
Model Stagnation Pressure Range (atm.).	0.003 to 0.025-----	0.015 to 0.10----	1 to 10.
Mach Number-----	3.0-----	3.0-----	3.0 to 3.5.
Run Time-----	Continuous-----	Continuous-----	Five Minutes.
Operating Gas-----	Nitrogen, Argon, Simulated Air.	Same-----	Same.
Electrodes-----	Water-Cooled Tungsten and Copper.	Same-----	Same.
Contamination Rate--	Less than 0.1 percent--	Same-----	Same.

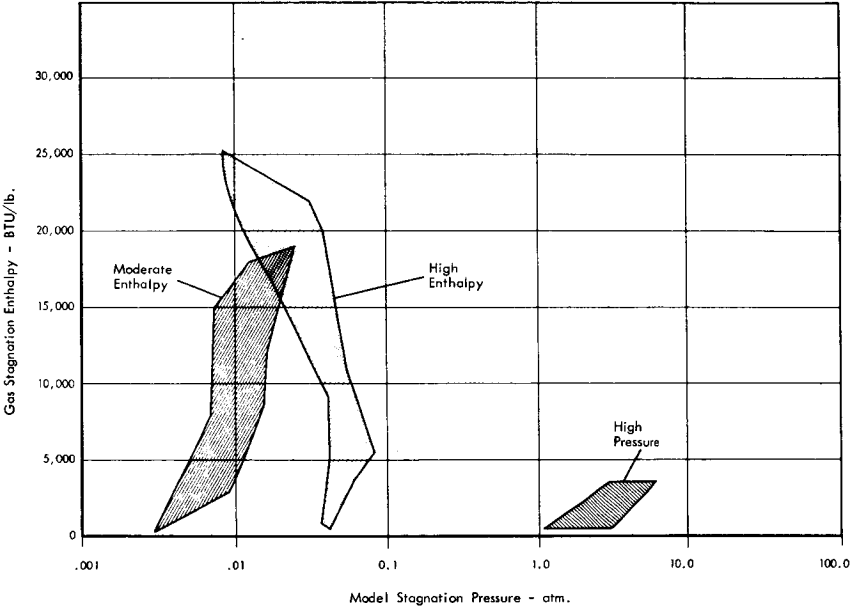


FIGURE 2.3.—Operating regimes for hyper-thermal reentry simulation facilities.
Courtesy of Plasmadyne Corporation

In addition to these three basic facilities, three vortex-stabilized radiation sources are currently being installed for the high-enthalpy chamber to simulate reradiated energy created by the free-flight shock wave in actual flight. This is of particular importance in the simulation of parabolic reentry conditions. In early 1964, the first com-

plete parabolic trajectory simulation incorporating both radiative and convective heat transfer environments was conducted.

For each simulated flight condition, certain gas-dynamic and gas-kinetic parameters are measured to provide calibration and knowledge of the environment sufficient for analysis of the model test results. Among these measurements are those parameters necessary for calculating the mean enthalpy of the jet (working gas flow, electric power input, and the power carried off by the cooling water) and the mixing chamber and nozzle exit pressures. The model stagnation pressure is determined with a water-cooled pitot probe directly sensing the total pressure behind a normal shock. Heat-transfer measurements with hemisphere calorimeter (steady state) are also taken.

From the model performance in these well-defined environments, it is possible for the materials engineer to predict performance under actual flight conditions. This results in considerable savings in money and time.

THE FUTURE

The attainment of the "parabolic" reentry simulation marks a significant point in the advancement of arc-tunnel technology. With the increased understanding of arc processes resulting from the analytical and experimental work carried out, it is reasonable to expect that future arc generators and arc facilities can exceed the parabolic enthalpies and pressure levels thus far achieved.

It may be anticipated that better simulation of all parameters is possible. The ability to produce more realistic conditions on larger and larger models is of paramount importance. Model size, to an appreciable extent, depends on input power. One must progress cautiously, however, for unless comparable or improved simulation is possible, the advantage of larger model testing will be of questionable value.

Future applications for high-pressure facilities include rocket-exhaust simulation and LORV (low observational re-entry vehicle) nose cone evaluation. Some efforts to utilize plasma generators to produce rocket exhaust environments are already underway, and considerably more work will undoubtedly be accomplished in the future. The unique ability to almost independently vary parameters such as gas temperature, pressure, and composition will provide the materials engineer with a tool by which he can isolate the variables which he must accept "en masse" in an actual rocket firing.

FURNACES

Using plasma torches for crucible melting was suggested several years ago, but large furnaces have been so powered only recently.

Furnaces of 50 kw. were built initially, and 200- to 300-kw. and 1,000-kw. units are in pilot production. There has been some speculation that a 10,000-kw. furnace will be built, but it would appear that there are more large-volume applications for the smaller units.

The basic advantages of the process include:

1. No carbon contamination.
2. Fast melting rates.
3. Inert atmosphere—vacuum-quality melts without the complications that accompany vacuum operation.
4. Stable power—less voltage fluctuation.

The greatest potential application for plasma furnaces lies in the region between induction and vacuum furnaces. The initial cost of the plasma furnace is much lower than the initial cost of vacuum furnaces. Many alloys now are being melted in vacuum which can be melted satisfactorily at atmospheric pressure with plasma.

Heat treating is another application of the plasma furnace. The transferred arc can produce heat-transfer rates much higher than any other known heating device. Flame hardening and annealing at high speeds have been accomplished experimentally, but it will probably be another one or two years before there is any large-scale use of these processes.

FURNACE HEATING

The low-velocity transferred arc is being applied to furnace melting in a controlled atmosphere, and at least one company markets equipment of this type.

In order to provide rapid heating of furnace charges, one firm reportedly has adapted a large transferred-arc gun for furnace melting of specialty alloys. The claim was made that this process will produce less alloy loss than vacuum melting the charge. Figures released to date seem to bear out this claim. From the manufacturer's analysis of an AISI 4130 melt, it was found that the gas content was significantly lowered. The analysis showed 8 to 25 ppm oxygen, 1 to 2 ppm hydrogen, and 10 to 30 ppm nitrogen.

The stirring of the melt is accomplished by means of a magnetic coil as in advanced vacuum-induction furnaces. In this case, the current feeding the gun is also passing (in series, it is presumed) through the stirring coils. This method is the technique used for arc "foot-point" rotation in large nontransferred arc plasma generators. A more flexible method would be the one in which the rate of stirring can be varied independently of the rate of heating. The literature states that the temperature of the melt can be maintained at a predetermined fixed value while stirring takes place at its required rate depending on any final alloy additions, etc.

Direct heating of atmospheric-pressure furnaces appears to be a logical application for the induction plasma generator which can produce large-diameter hot zones of low-velocity gas with gas flows no larger than purge rates now used in inert-atmosphere resistance-heated furnaces. Experiments have been conducted, but no reduction to practice has been made. It is expected that a limited amount of equipment will be available in this area within the next five years.

PLASMARC FURNACE²

Plasmarc³ melting is the utilization of a direct-current transferred arc which is directionally controllable and stable. This arc, when operated in an inert-gas atmosphere, is a clean and uncontaminated source of heat. Generally, Plasmarc melting is employed with metals. Preliminary results show that the products of this process are of the highest quality, and their physical properties are equal to those of vacuum-melted material. This melting method appears to be widely applicable.

The furnace hearth design is similar in shape to that of conventional graphite-electrode furnaces and the same refractory materials are used. The furnaces are connected to the charge electrically through a water-cooled bottom electrode mounted flush with the inner surface of the hearth. To prevent contamination of the atmosphere over the metal bath, the furnace-roof side-wall joint is sealed with a labyrinth sand seal. When the furnace is operating, the spout is covered, a gas-tight cap is clamped over it, and chevron rings are used to seal against the torch mounted in the center of the roof (Figure 2.4).

In order to insure the chemical and temperature homogeneity of the molten bath as well as to aid rapid melt-in, the furnace is equipped with two conductive stirring coils connected directly to the bottom electrode. The magnetic field from these coils, interacting with the magnetic field of the plasma, causes the molten metal bath to be stirred gently. The coils operate on the direct current of the arc and do not require auxiliary controls or equipment of any kind.

Figure 2.5 shows the torch designed to be used in the furnace for melting metals. This torch achieves arc stabilization by means of an inert gas such as argon flowing around a water-cooled, nonconsumable, tungsten-alloy electrode. The electrode is protected from molten metal splash by a water-cooled copper nozzle. The combination is simple and rugged and has operated over a period of more than 100 hours without requiring maintenance. The argon flow used to stabilize the arc also acts as the source of inert gas to maintain the required

² Most of this material was prepared by R. J. McCullough of the Linde Corporation.

³ Trademark used by the Linde Corporation.

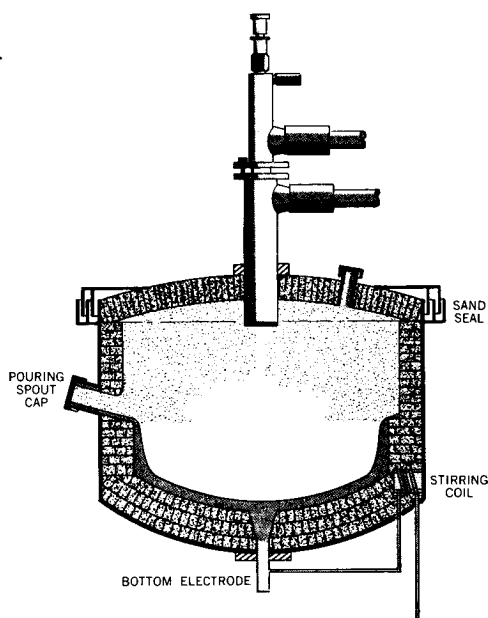


FIGURE 2.4.—Typical Plasmarc furnace.

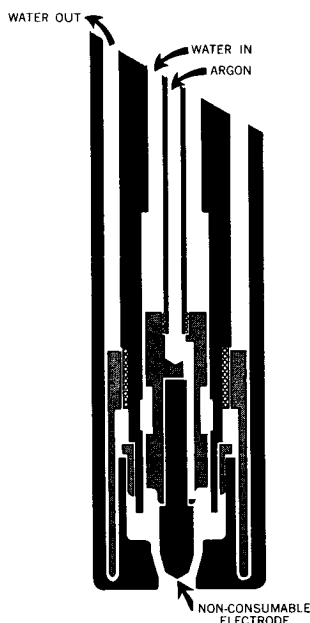
Courtesy of Linde Corporation

FIGURE 2.5.—Water-cooled Plasmarc torch.

Courtesy of Linde Corporation

furnace atmosphere. The effluent gas escapes from the furnace by flowing through the sand seal at the furnace roof.

The electric arc in this specially designed plasma torch has inherent electrical stability. Melting of well over 100 heats has not resulted in a single instance of short circuiting or the associated heavy current surges so damaging to equipment. Figure 2.6 illustrates graphically the fundamental stability of the arc.

The advantage accruing to a furnace operator of utilizing a stable arc in an inert atmosphere is that the rate of energy input to the furnace may be closely controlled and maintained at a maximum level without fear of rapidly changing voltages which would result in power supply damage. Any desired energy input rate may be easily achieved and controlled during any portion of the heat.

In addition to the high degree of power control available, the use of a nonconsumable tungsten-alloy electrode eliminates a possible source of carbon pickup by the melt.

This torch can bore a narrow hole into the charge material; molten material collects at the bottom of the hole. The arc melts the scrap along its length only by radiant energy from the arc and not by direct arc contact with the charge. The anode spot at the base of the hole

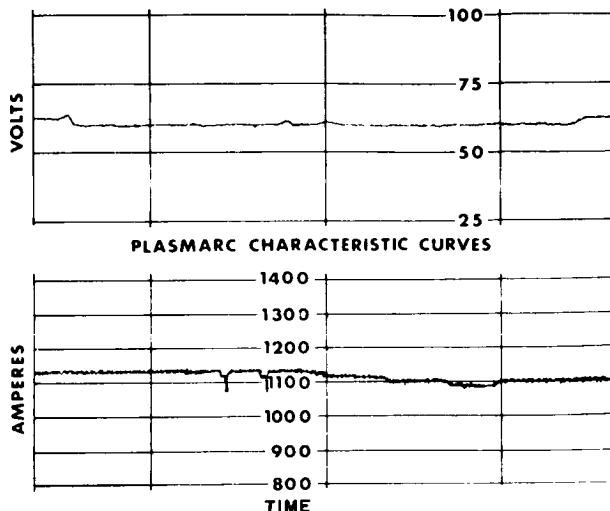


FIGURE 2.6.—Arc stability.

Courtesy of Linde Corporation

superheats the small molten pool, and its contact with the unmelted portion of the charge transfers heat by conduction. The energy transfer by arc radiation is less than that transferred at the anode spot; hence, the melt proceeds more rapidly from the bottom upward. This bottom-up melting is advantageous in that energy radiated from the bath is received by the charge, thereby accelerating melt-in and protecting the refractory from arc exposure in early periods of the heat. Unlike graphite electrode operation, the torch does not have to travel down the bored hole but can remain stationary. This eliminates the danger of electrode breakage from collapse of heavy scrap, short circuiting by scrap contact with the electrode, and, of course, carbon pickup.

To maintain the arc circuit, the arc must contact the charge of molten material which in turn is in contact with a bottom electrode. An exposed hearth cannot be damaged by the arc since an exposed hearth is a discontinuity in the arc circuit.

The absence of arc flare caused by the interaction of the unstable arcs and their magnetic fields during and after melt-in eliminates hot-spot erosion of furnace refractory which is normally experienced in standard electric furnace practice.

PLASMA-JET REFRACTORY FURNACE

Scientists at the Research Institute of Temple University in Philadelphia are making investigations beyond $5,000^{\circ}$ K. (the existence range of chemical compounds). Results of these investigations may provide information crucial to many advanced concepts in space pro-

pulsion and allied fields. The development work provides a route to extend research on chemical reactions in the liquid phase to a much higher temperature range than was previously possible.

The Temple University scientists are also conducting high-temperature studies of the chemical behavior of liquid elemental metals beyond the practical limits imposed by solid refractory containers. This method involves the combination of a noble-gas plasma-jet and a centrifugal furnace (Figure 2.7). The substance under research floats on a bath of refractory material held against the outer rim of the circular furnace by centrifugal force.

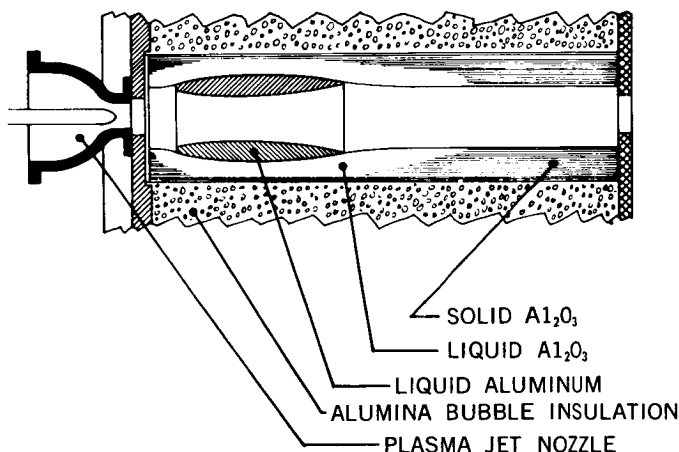


FIGURE 2.7.—Centrifugal furnace.

Courtesy of Temple University

A major disadvantage of the chemical furnace is its need to be coupled to an exothermic chemical reaction, rendering it impossible to study anything but the reaction taking place. Temple University researchers eliminated this problem by employing a plasma jet as the heating source. In order to operate in the $5,000^{\circ}$ to $15,000^{\circ}$ K. range, a noble gas such as helium or argon was used.

Temple's furnace is a steel cylinder about 12 centimeters in diameter surrounded by a water jacket. The unit is rotated on ball bearings by a 1-horsepower drive motor with a range from 500 to 1,500 r.p.m.

The interior of the cylinder can be filled with any suitable insulation material. Several coaxial tubes of any oxide or graphite make up the reaction section.

FURNACE OPERATION

The plasma jet was used to heat and melt an Al_2O_3 tube. An exit port was available for viewing the liquid oxide. A solid rod of alumi-

num of known weight was introduced at a slight angle through the exit port. The rod melted in a few seconds and the molten aluminum floated on the liquid oxide; it came to a boil in three minutes and distilled through the exit port. The process was run at a pressure of one atmosphere.

When the furnace cooled, it was discovered that the innermost oxide tube had melted over a length of about 10 cm. All the remaining aluminum metal formed a sharp cylindrical band on the Al_2O_3 . The band was about three centimeters in width and approximately three millimeters thick. Both phases were perfectly defined and separated. A tube of thorium oxide also has been melted.

By operating the plasma jet and the furnace at a higher total pressure, the ratio of the vapor pressure of the container to the total pressure can be adjusted as desired. This process is not particularly suited to determining physical properties such as density and electrical resistivity because of imperfect geometry. However, these measurements can be made in a centrifugal furnace heated by ohmic resistance.

LIQUID CONTAINER FOR HOT METALS

Also in work at Temple's Research Institute, centrifugal force helps hold metal at temperatures above the liquid container's melting point. As a result of this work, liquid-phase chemical reactions up to $4,000^\circ\text{K}$. can now be sustained for 15 minutes.

A plasma jet of either argon or helium is used as a heat source to provide temperatures between $10,000^\circ$ and $17,000^\circ\text{K}$. A cylindrical rotating furnace that contains the materials to be studied surrounds the jet.

The centrifugal furnace has a reaction section composed of concentric tubes (usually three). Depending upon the material to be melted and the reaction itself, the tubes are made of oxides, carbides, nitrides, or graphite. Insulating materials—often of alumina—surround these tubes.

A steel cylinder about 12 centimeters in diameter holds the tubes in place. The cylinder is surrounded by a water jacket, and both ends of the cylinder are fitted with ball bearings that support it while it rotates from 500 to 1,500 r.p.m. The speed of rotation depends on the materials involved.

One end of the furnace is open; the other end is fitted with slip-fit gas inlets for the helium (or argon) used for the plasma jet. As the material melts and finally boils, it pours out through the open end, reacts with oxygen from the surrounding air, and burns. In another method the vapors may be collected and crystallized in a stationary tube.

The concentric reaction tubes can be made of alumina when aluminum is the test material. Furnace rotation is started and the plasma jet turned on. A section of the reaction tube is melted in two or three minutes. Pure aluminum, perhaps as a rod, is placed in the heating zone where it melts and falls on the already liquid alumina of the reaction tube. There the aluminum is brought to the boiling point.

The melted alumina forms a liquid layer on itself in the melt area because of the centrifugal motion of the furnace. This makes up the liquid crucible. The melted aluminum, in turn, lines the melted alumina because of density difference. At 2720°K . the specific gravity of liquid alumina is 2.569, that of liquid aluminum is 2.050.

If the plasma jet is turned off and the furnace allowed to rotate while cooling, the aluminum solidifies on the alumina in the heat zone. Both materials remain separate and distinct from one another.

A centrifugal reactor may be used for containment under the following conditions:

1. The density of the container must be greater than that of the liquid metal. If the metal does not float in the container, the liquid container will not work.
2. A material must be chosen that either does not react, or reacts only slowly with the liquid metal (for example, alumina is used with aluminum).
3. The container should be a reasonably good thermal insulator (liquid metal oxides). The containing material melts at the liquid-metal interface, thus producing within itself a solid-to-liquid continuum that serves to contain, support, and thermally insulate the liquid metal.

Some experiments with other materials have been completed by the Temple University researchers. Iron may be boiled in a liquid thorium dioxide container. Containers have been made of tantalum carbide and beryllium and zirconium oxides as well as of a wide assortment of other oxides, nitrides, carbides, borides, and silicides.

The technique for using the centrifugal furnace and plasma jet evolved from earlier work in which exothermic reactions, such as the oxidation of aluminum to alumina, were used as the source of heat. Heat sources employing chemical reactions have the disadvantage of restricting the choice of reactions to be studied. Contamination of the test reaction is another problem. Noble gases in the plasma jet prevent these problems and make provisions for tremendously high temperatures as well.

The technique offers a possible way to contain reactants at high temperatures with little or no reaction between the container and the

subject material. Also, it provides an opportunity to study reactions that might occur at temperatures where containment was not heretofore possible.

HEATING APPLICATIONS

The plasma flame produces heat-transfer rates 5 to 10 times that of the conventional oxyacetylene flame and is competitive from an economic standpoint. This plasma flame produces a Btu of heat at less cost than an oxy-fuel gas flame. In addition, completely controlled atmospheres can be obtained, and gas can be recycled, thus reducing operating costs still further. Years of field testing and actual use have resulted in completely reliable industrial equipment, now available in a wide range of power levels up to 1,000 kw.

TABLE 2-I.—*Comparison of Hourly Operating Cost of Oxyacetylene and plasma flames.* Table 2-II compares parameters for various common heat sources and the plasma flame.

TABLE 2-I.—*Comparison of Hourly Operating Cost of Oxyacetylene Flame and Plasma Jet*

Courtesy of Thermal Dynamics Corporation

Assumed oxygen flow-----	625
Acetylene for stoichiometric combustion-----	250
Heat generated by combustion (LHV-1453 Btu/ft. ³)-----Btu/hr--	361,000
Equivalent electrical power in plasma-jet flame-----	106
Power to torch at 65 percent efficiency* 106/.65 x .70-----	255
Nitrogen gas flow to torch-----	300
Temperature oxy-acetylene flame-----°F--	5,600
Temperature plasma jet-----°F--	11,000
<hr/>	
Operating Cost Plasma Jet:	
Power at 1.5¢/kw.-hr. (0.015 x 255)-----	\$3.83
Nitrogen cost at 1.5¢/ft. ³ -----	4.50
<hr/>	
Total operating cost-----	8.33
<hr/>	
Operating Cost Oxyacetylene Burner:	
Oxygen at 1.5¢/ft. ³ -----	9.38
Acetylene at 2.0¢/ft. ³ -----	5.00
<hr/>	
Total operating cost-----	14.38

*Use of a motor generator or selenium rectifier ac converter requires that an additional efficiency of 67 to 75 percent must be applied.

TABLE 2-II.—*Approximate Comparison Heat Source*
Courtesy of Thermal Dynamics Corporation

Type of Source	Temp. °F.	Velocity fps	Heat Trans- fer Rate to Object in Flame Btu/in. ² -sec.
Air-Fuel Bunsen Flame-----	3, 000	20	0. 5
Oxygen-Acetylene Welding Flame-----	5, 600	400	5
Plasma Jet-----	10, 000	1, 800	45
Welding Arc-----	20, 000	20	70
Plasma Flame Metal Cutter-----	40, 000	15, 000	250

RADIATION SOURCES

The radiation source manufactured by Plasmadyne combines the most advantageous features of the vortex-stabilized arc-jet and the high-pressure, short-arc lamp. A typical unit (Figure 2.8) consists of a fused-silica cylinder and two water-cooled conical electrodes aligned on a common axis. The working gas is introduced tangent to the inside circumference of the fused-silica cylinder and forms a vortex as it spins to the central axis, exhausting through a drilled hole at the anode tip. The gas then moves through a heat exchanger, a recirculating pump, a filter, and then back to the tangential openings in the arc chamber.

Operation of the radiation source under properly regulated power and gas flow produces a cylindrical arc plasma stream with a diameter approximately two-thirds that of the anode exhaust aperture.

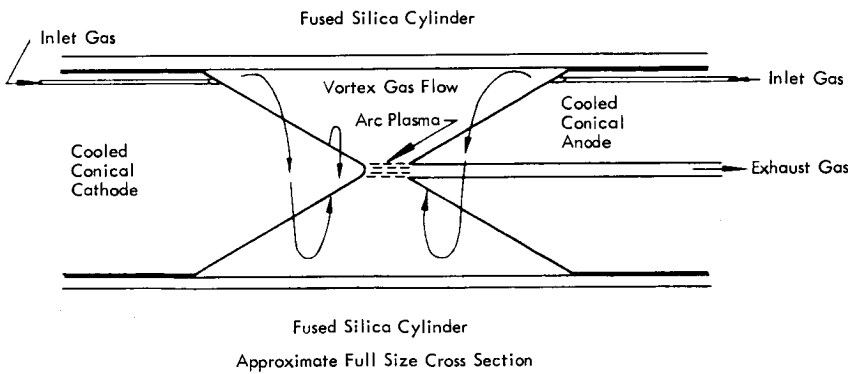


FIGURE 2.8.—Vortex stabilized radiation source.
Courtesy of Plasmadyne Corporation

This particular type of radiation source presents significant technological advances in four important areas:

1. The source unit can use a variety of gases or mixtures of gases. This feature permits control of spectral energy distribution in the radiation produced.
2. Units can be designed for very large power inputs and operation over a wide range of power levels.
3. The cool vortex flow continually replaces the gas surrounding the arc, thus greatly reducing red and infrared radiation when compared to other enclosed arcs. Also, the vortex "fixes" the arc plasma diameter and precisely locates the arc column.
4. The unit can be built to operate in any attitude and in any environment from a liquid, such as sea water, to the vacuum of space.

Vortex-arc units have been successfully operated with helium, neon, argon, krypton, xenon, nitrogen, and various mixtures of these gases. Argon has been used most frequently due to its relatively low cost and its interesting intensities in the ultraviolet. Typical performance of an argon vortex source is indicated below:

Operating gas.....	Argon
Arc plasma dimensions.....	10 mm. x 3 mm.
Input power.....	24.8 kw.
Arc chamber pressure.....	17 atmospheres
Usable radiation solid angle.....	≈10 steradians
Plasma temperature.....	>7,000°
Luminous Output:	
Candle power.....	42,200 c.
Average brightness.....	1,400 c./mm. ²
Efficiency	17 lumen/watt
Total Radiant Output:	
Radiant flux.....	7.68 kw.
Efficiency	30.9 percent
Ultraviolet output 200 to 400 mμ.....	2.6 kw.

The detailed spectral energy distribution curve for the vortex-stabilized radiation source, operating with argon at 24.8 kw. and 17 atmospheres, is shown in Figure 2.9. A study of luminous output using argon at different power settings is given in Figure 2.10. To obtain these data, power and gas flow were controlled to maintain plasma diameter constant at 3 mm. This establishes a constant source area, and is essential to successful operation of the light source. It is evident that not only candle power increases with input power but also the plotted candles-per-kilowatt variable shows a large increase with power input.

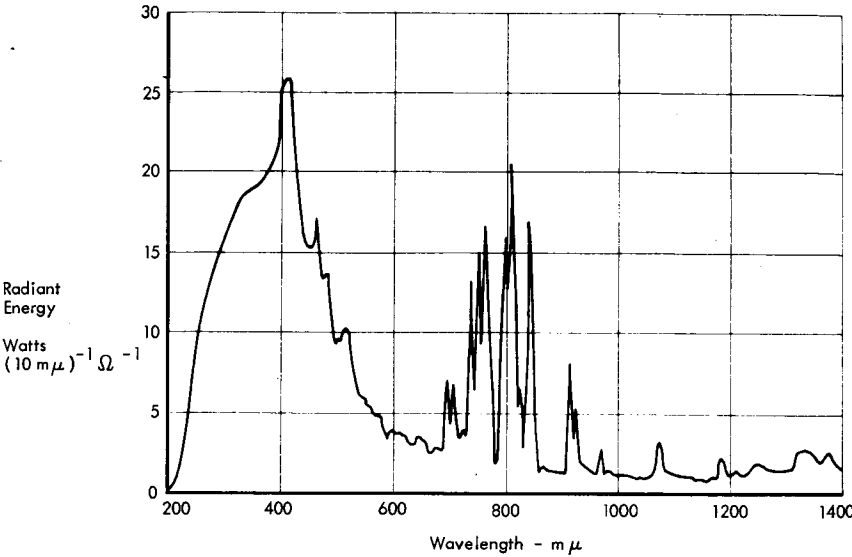


FIGURE 2.9.—Spectral energy distribution argon.
Courtesy of Plasmadyne Corporation

VORTEX STABILIZED RADIATION SOURCE

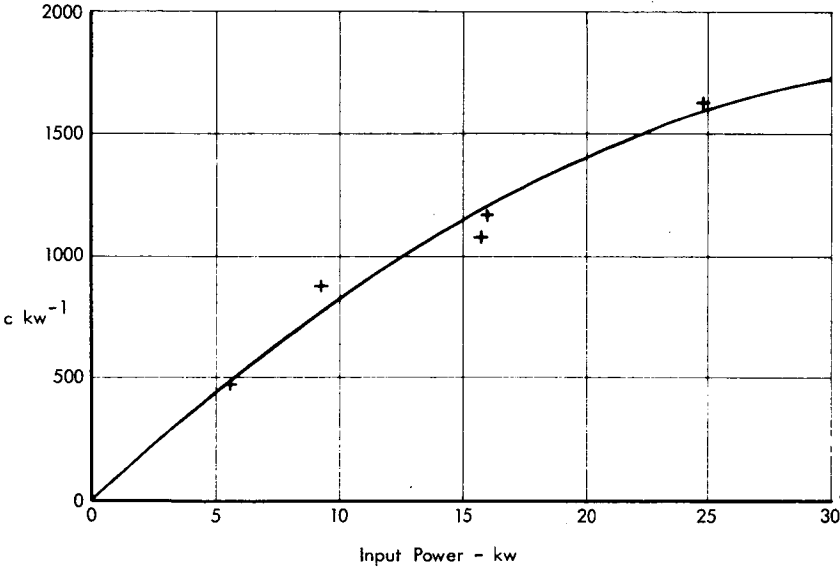


FIGURE 2.10.—Candles per kilowatt (arc plasma diameter constant).
Courtesy of Plasmadyne Corporation

The VSRS (Vortex-Stabilized Radiation Source), using xenon as the working gas, had been operated to about 10-kw. input power up to late 1963. Brightness is 50 to 100 percent greater than the brightness using argon. However, mixtures of small amounts of xenon with argon show increased brightness. As development continues, a brightness of 5,000 c./mm.² and luminous efficiency of 60 lumen/watt are likely to be achieved with high-power operation.

The integration of the VSRS to various radiation (ultraviolet, visible light, and infrared) source applications will require good optical design to utilize the large solid angle available from the unit. Figure 2.11 exhibits a spherical reimaging mirror which allows nearly complete collection of the source radiation with the output beam formed by a paraboloid or ellipsoid. An important advantage of the VSRS is immediately apparent when such an optical design is studied. The arc is precisely located by the vortex flow and this in turn is located to machine shop tolerances during construction of the source. Optical systems may therefore be assembled without time-consuming adjusting and focusing.

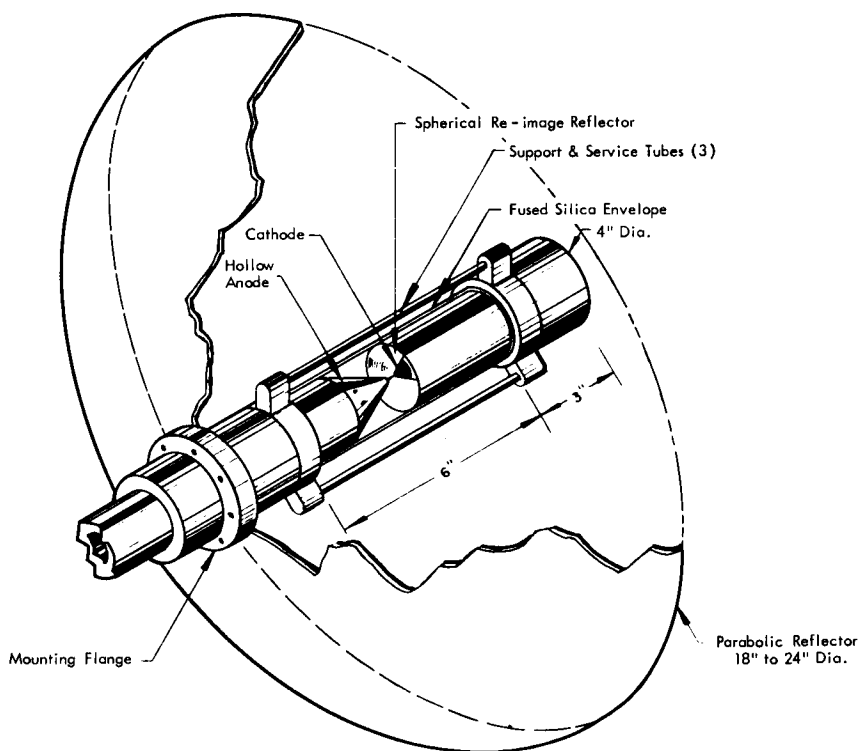


FIGURE 2.11.—Vortex stabilized radiation source.

Courtesy of Plasmadyne Corporation

It is apparent that there are many applications for a source of this type. A number of these are of an immediate nature, while others will likely require additional optimization of the source and/or its associated equipment. Several of the more pertinent applications are listed below.

Immediate Applications:

- Solar Simulation ⁴
- Arc Image Furnaces
- Photochemistry
- Photoreproduction ⁴
- Illumination (flood or beams) : ⁴
 - Ultraviolet
 - Visible
 - Infrared

Applications Requiring Optimization of Source and/or Associated Equipment:

- Laser Pumping
- Optical Communication :
 - Ultraviolet
 - Visible
 - Infrared

The application of the VSRS to any of these uses is particularly interesting because of the very high power levels that can be maintained. Units have been operated to 100-kw. input power resulting in the availability of 30 to 40 kw. of radiant power. The VSRS, a plasma device, represents a definite advance in the state-of-the-art for projection of visible and near visible radiation for a wide variety of applications. TAFA (a Division of Humphreys Corporation) has also marketed a plasma light source similar in performance to the VSRS, but one that—differing in the reactive as well as inert gasses—can be used to vary the possible emission spectrum. Westinghouse also has recently announced the development of intense light in the 15-kw. range.

COATING AND SPRAYING

The introduction of the modern nontransferred-arc plasma torch in the late 1950's provided industry with a new heat source for continuous generation of extremely high temperatures. The field of metal and ceramic spraying was a natural outlet for such a device since it

⁴ The Vortex Stabilized Radiation Source is available and advantageous for this application immediately. It is likely, however, that additional optimization of the source for this specific application will result in even greater advantages than now exist.

widened the scope of sprayable materials to include some which otherwise could not be considered because of their high melting points. Many of the oxides, carbides, borides, and nitrides fall in this category.

Plasma equipment manufacturers were quick to point out that temperatures in the plasma flame were an order of magnitude greater than acetylene combustion and that all materials with a well-defined melting point could now be sprayed. Coating quality has been inadequate with many of these new materials, however, because of poor particle melting, a factor which led to disillusionment on the part of some users. In fairness to the equipment manufacturer, it should be pointed out that the demands of industry for new material and higher operating temperatures prompted sales on potential rather than on proved performance. It appears that the industry has now stabilized itself and that plasma spraying can enjoy a gradual increase of usage in the broad spectrum of the metal and ceramic spraying industry.

BONDING THEORY

Bonding mechanisms can be classified rather arbitrarily as "microbonding" and "macrobonding." Microbonding refers to the bonding that takes place on a very small surface area the size of an individual particle of sprayed metal. These particles are of the order of one to a few square mils in area. Macrobonding refers to much larger areas, larger perhaps by 10 to 100 times. Macrobonding relates to the macro-roughness produced by threading and grooving methods, or by extremely rough grit blasting.

The microbond between sprayed metal particles and the base material, and between sprayed metal particles, is never completely mechanical. In photomicrographs of sprayed metal the laminated particles look like fish scales or saucers, rather than like hooks. Frequently there are no microhooks. It is a well-known fact that often a few particles of a sprayed material will stick on a smooth surface, some very tightly. Some years ago, when one company was making molds by spraying on a form and using the shell of sprayed metal, it frequently found that it could not remove a thin coating from the form, but had to build up a relatively thick shell before it could be removed. This experience is mentioned to point out that there may be considerable bonding between particles at the microbond level, and no bond at all over a macro area after a substantial coating has built up. The reason, of course, is shrinkage.

As each particle strikes it flattens out, sticks to some extent, and then shrinks. A first shrink results when the particle changes from a plastic to a solid state. This corresponds to shrinking in a casting. In addition to the state-change shrink, there is normal thermal shrink which continues as the particle cools after "freezing." At the particle

level, shrink may not cause much stress, or at least not enough to rupture the microbond. The preponderance of evidence indicates a strong initial film adhesion between the sprayed particles and the base, and between one sprayed particle and another.

This microbonding mechanism is still not clearly understood and does not have a commonly used name. It is the same adhesion which occurs between an anodized coating and aluminum, or between chrome plate and steel in an automobile bumper. This adhesion has been variously referred to as "film adhesion," "physico-chemical bond," and most recently by physical metallurgists and solid state physicists as "solid-phase bond" or "solid-state bond." The bond may be very strong, nonmechanical, and of molecular size, but it is not usually referred to as "metallurgical." In the art of welding and brazing, metallurgical bonds involve some alloying of the materials at the interface. Industry is adopting the convention that a bond is not metallurgical unless there is sufficient interaction of the materials at the interface to produce an alloy layer.

Particles of most flame-sprayed materials bond, more or less, to the base material and to each other by film adhesion. Wire particles bond by both film adhesion and by metallurgical bond, but much of the bonding between the wire and the base material, and probably all of the adhesion between one bond particle and another, may be of the film-adhesion type. In the case of nickel aluminide, however, the exothermic reaction causes an alloying of the materials at the interface and the result is a true metallurgical bond.

TECHNIQUES⁵

Design improvements in plasma flame-spray hardware recently have been primarily in the area of increased reliability, increased speed and deposit efficiency, and in the development of auxiliary equipment. Such equipment includes extensions for spraying down into holes, argon flooding devices for obtaining results comparable to inert gas chamber spraying in the open atmosphere, and CO₂ cooling devices. A typical torch design is shown in Figure 2.12 and the entire system in Figure 2.13.

Aside from dramatic improvements in speed and deposit efficiency, and hence in economy in the plasma flame spray process, the major recent developments have been in coating systems rather than in hardware. This work has resulted in the development of a number of specialized materials for plasma flame spraying. The most important development has been that of a synergistic process for spraying materials which combine exothermically during the spraying process to pro-

⁵ Much of this information was provided by Metco, Inc., 1101 Prospect Avenue, Westbury, L.I., New York.

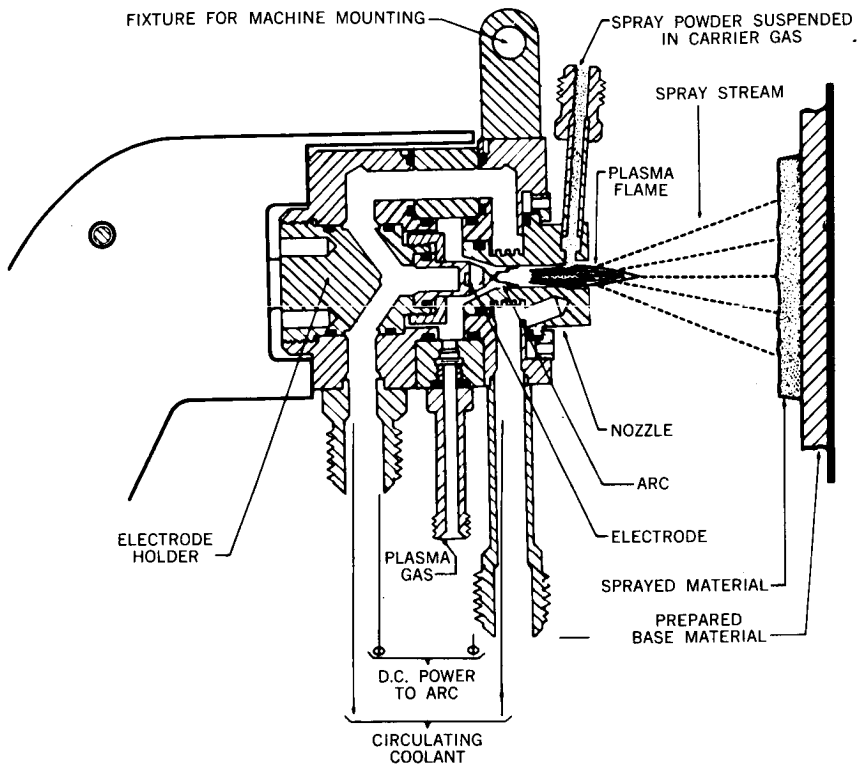


FIGURE 2.12.—Plasma flame spray gun cross section.

Courtesy of Metco

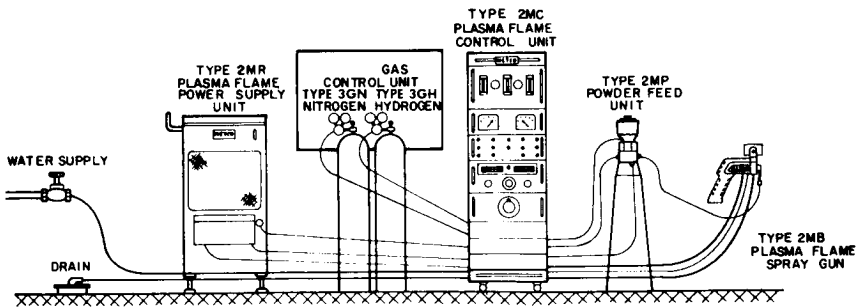


FIGURE 2.13.—Plasma flame spray system complete installation.

Courtesy of Metco

duce coatings comprising intermetallic compounds of the component material.

One of the first big technological breakthroughs in plasma was the development of the high-enthalpy, laminar plasma flame. This mode of operation is noiseless and requires a very small amount of gas flow. Furthermore, it lengthens the hot zone or core of the plasma and extends it outside the nozzle where more efficient use can be made of the heat. Operating costs are immediately lowered by the reduction of gas flow, and particle melting is assured. The high-enthalpy flame has been used primarily for making spherical particles rather than for spraying since the gas momentum is too low to accelerate the particles sufficiently. A secondary air blast is required to impart the necessary momentum to achieve proper utilization of the high-enthalpy flame for spraying. It is significant to note that the laminar flame can melt particles from 0.012 to 0.015 inch in diameter, a size range not affected when injected into a standard plasma flame.

Transferred-arc deposits were first investigated to fill the requirement for a metallurgically bonded coating. In actual operation, the process system consists of two arcs powered by two separate power sources (Figure 2.14). Gas flow is lowered to produce a low-momentum, laminar flame, controlled within the nozzle (one power supply) to melt the powder, while the second power supply heats and puddles the base. The dilution of the deposit into the substrate can be maintained at a low level. In addition the process offers the advantage of being very adaptable to automatic setups. The latter is possible because the transferred-constricted arc with low-gas flows is less susceptible to variation in workpiece distance than conventional open arcs. To date, the self-fluxing alloys have given the best results, thereby eliminating the two-step process of spraying and fusing. The process is similar to hard-facing rather than spraying and has great potential when used with rod-and-wire feeding devices.

Higher velocity plasmas are needed to meet the challenge of the higher density detonation coatings. The demands for high heat fluxes and pressures to simulate orbital reentry conditions have led to the development of high pressure plasmas operating up to 100 atmospheres prior to expansion. Present plasma-spraying torches operate at a gauge pressure of one-half an atmosphere and cannot be increased with standard electrode geometries without rapidly deteriorating the tungsten cathode. The enthalpy of the flame must be maintained, or increased, at higher pressure since the dwell time of the particles within the hot zone is reduced as gas velocity and density increase. To compensate for the reduction in dwell time, it is necessary to use finer powders, lower feed rates, and higher powers. A

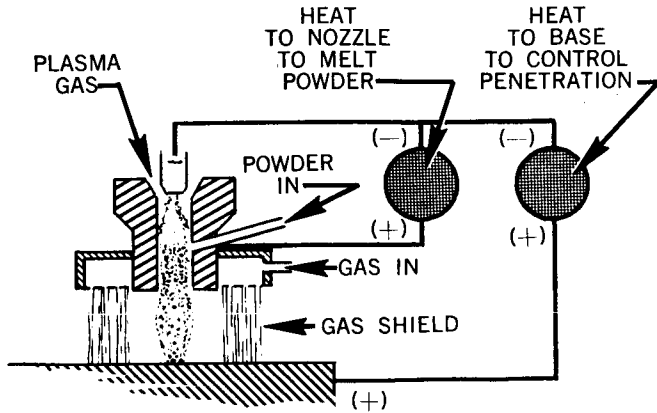


FIGURE 2.14.—Transferred arc process.

Courtesy of Thermal Dynamics Corporation

torch operating at 50-kw. with 3 to 4 atmospheres of pressure has produced coatings substantially superior to conventional coatings. The next step in this direction will be to feed powder into a torch operating at 25 to 50 atmospheres and 200-kw. A torch of this magnitude would only be suitable for machine mounting, but should produce coatings with densities and bond strengths superior to those produced by standard plasma torches.

Plasma jets larger than 200-kw. have not found application in flame spraying to date. Most interest has centered around hand-held or lathe-mounted units in the 20- to 60-kw. range. Production pieces are being sprayed, from large rolls for paper mills (coated with tungsten carbide) to piston rings, valve slots, nuclear control rods, gas turbine blades and rocket nozzles coated with tantalum-titanium carbide mixtures, or tungsten and its alloys.

A good plasma-arc coating is generally characterized by a strong bond between the particles and by chemical properties consistent with those of the parent material. Nevertheless, a typical coating generally has considerably less strength than the parent metal in bulk form, mainly because the coating is essentially composed of frozen droplets in a quenched condition. For example, a coating such as tungsten, with a density 80 to 90 percent of theoretical, has a bond strength of about 1,000 psi and a tensile strength of 5,000 to 10,000 psi (as compared to 180–200,000 psi for cold-worked tungsten).

Reduced strength, however, is often not a critical limitation because sprayed materials ordinarily depend on the base metal for support. Also, strength is often not the dominant selection factor; some other property may be desired.

In some special coating applications, mechanical and physical properties can be substantially improved by heat treatment. For example, densities up to 99 percent of theoretical can be obtained with some materials after heat treating.

Plasma-arc coatings can be used for many wear-resistant applications and can often replace wear-resistant inserts and electroplated or hard-faced (welded) surfaces. They are particularly suited for light metals such as aluminum, magnesium, titanium, and beryllium because they greatly improve wear resistance without affecting other desirable properties.

Although many coating materials can be used for wear resistance, the most common are carbides, cermets, oxides, and hard metal alloys. These coatings are particularly useful in minimizing metal-to-metal wear and in providing compatible mating surfaces. Coating systems are available with low coefficients of friction and antigalling properties. However, plasma-arc coatings are not usually recommended where the coating particles will be subjected to high-velocity particle erosion. Carbide cermets, in particular, have a tendency to fail from selective erosion of the softer matrix material and subsequent loosening of the hard particles.

The coatings have been successfully used on very small and very large areas—from small gauges to large machine parts. They are not particularly suited for cutting edges or where high point loading is present, as in die edges, and they are not recommended where very heavy wear or high impact is encountered, as in mining and construction equipment.

In general, the best thermal resistance is provided by the oxides because of their low thermal conductivity. Metals have better resistance to thermal cycling, but some erode in oxidizing atmospheres.

Although the refractory oxides have excellent resistance to high heat flux, their relatively low expansion characteristics promote loss of adhesion when they are used over high-expansion metals, such as nickel alloys, during thermal cycling. Undercoating with an intermediate material or grading the coating from one material to another may help.

Coatings applied by the plasma arc are not generally suitable for improving resistance to corrosion and chemical attack. Even the best such coatings have some porosity and permeability and will permit passage of fluids, vapors, and gases.

Adequate protection can be obtained, however, when the surface tension of the corrosive fluid is such that there is no capillary transfer through the pores. Thus, the coatings have proved useful with molten metals. Nevertheless, selection is complicated by the fact that the

materials with the best resistance to attack—the refractory oxides—have low expansion characteristics and are not so likely to resist the thermal stresses encountered with molten metals.

Thin plasma-arc coatings can sometimes be impregnated with a plastic material to provide impermeability. Although this combination has a low upper temperature limit it can be useful where resistance to both moderate wear and chemical attack is needed.

The as-sprayed finish of plasma-arc coatings can be controlled from 75 to 250 microinches. However, metals and carbides can be ground to 4 to 10 microinches and ceramics can be ground to as low as 4 microinches.

It is good practice to keep coating thicknesses to a minimum. A thickness of 5 to 20 mils is normally sufficient. However, for special applications, coatings can be made as thin as 2 mils and as thick as 0.2 inch. However, the 0.2-inch thickness is obtainable only under ideal conditions. Coating dimensions can be controlled to as close as ± 1 mil on cylindrical surfaces and to as close as ± 2 mils on flat surfaces.

As shown in Figure 2.15 the key element in the plasma-arc process is a gun or torch containing a constricted direct-current arc through which an inert gas is passed. The gas is heated to extremely high temperatures—reportedly as high as 25,000° F.—and has a high thermal energy content and velocity.

Powder is injected into the hot plasma, or ionized gas, at the nozzle exit. Because of the great amount of energy in the gas, the powder melts almost instantly and the molten particles swiftly accelerate toward the surface. In order to prevent excessive heating of the base material, the high-temperature gas stream is deflected with a stream of cool air or an inert gas. This stream does not appreciably deflect the molten particles which have high velocity and momentum.

The coating can be considered to be in a state of internal tension, and occasionally it becomes so stressed that it tends to lift and separate from the base.

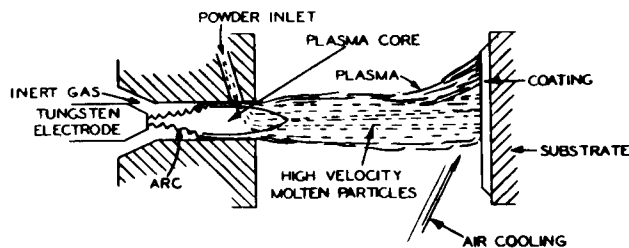


FIGURE 2.15.—Schematic nontransferred plasma arc-powder injection.

Courtesy of Valley Metallurgical Processing Company

In some cases it is desirable not to cause full melting of the coating particles. With certain cermets, for example, melting of the ultra-hard refractory particle can cause it to alloy with the matrix metal. The resulting alloy and new structure is likely to have considerably low hardness and other not-so-desirable properties.

Some materials, such as pure tungsten carbide, boron carbide, and other pure-metal carbides, have very poor quality as deposited. The particles are poorly bonded and can be easily penetrated even though the parent material is known to have extreme hardness. This weakness appears to be due to the inability of separate particles to wet one another.

The powders used in the plasma torch can have a great effect on coating quality. Better coatings are usually obtained with fine particle sizes. Cermet and multicomponent-materials powders should be presintered or prealloyed; with other materials it is generally desirable to use a fused or crystalline structure.

Good surface preparation is needed in order to maintain an intimate bond with the base. Surfaces are usually prepared by chemical cleaning and by surface roughening with a grit blast. Roughening increases the apparent surface area, provides anchor points, and exposes fresh material.

Although coatings can be applied to practically any solid material, very soft or extremely hard surfaces cause some difficulties. For example, a highly stressed coating on very soft surfaces will sometimes shear at the interface due to insufficient strength of the base material. This limits the types of coatings and thicknesses that can be used on base materials with low tensile strength or high elongation such as tin, lead, epoxies, and other plastics.

Good bonding on very hard surfaces is difficult to obtain because sufficient roughening cannot always be achieved. Special precautions are necessary with base materials that are particularly hard (e.g., ceramics) and with materials that cannot be annealed to reduce hardness without losing other desirable properties. However, in some cases adhesion can be promoted by an undercoat of molybdenum which has a unique ability to adhere to smooth surfaces.

Because the coating particles travel in a straight line, accessibility to recessed areas can be a problem. Thus, the plasma gun must be held at a high angle to the working surface. A good rule of thumb is that small internal diameters cannot be coated to a depth greater than the diameter; the thinner the coating the better. Conversely, undesirable overspray can be prevented easily by using tapes or special compounds. In light of the wide latitude of application parameters, considerable judgement is required by the plasma-gun operator.

COMPARISON OF PROCESSES

It can be safely stated at this stage that there is a good potential for plasma coatings, but usage is relatively small in comparison to the total amount of spray coating. In relation to the oxyacetylene process, plasma has made some inroads at the high-temperature end of the spectrum, or where standard coatings have been marginal or inadequate. In the case of detonation coating (Flame-Plating⁶), plasma has been substituted on a limited basis where low rms surface finish after grinding is not extremely important. It is apparent that plasma coatings must become more economical in order to compete further with oxyacetylene processes, and more dense and adhesive in order to compete with Flame-Plating or coatings employing metallurgical bonds.

In each instance, quality must be the determining factor. It is not practical to consider plasma coatings in place of an oxyacetylene sprayed coating (unfused) unless there is a requirement for an improvement in quality. Table 2-III is a compilation of data which compares plasma with oxyacetylene spraying, both the wire and powder feeds. The results of tests indicate that plasma coatings, with the exception of molybdenum, may be superior to flame-sprayed coatings. Conversely, substitution of plasma spraying for detonation coating is unrealistic if a decrease in quality will lead to premature failure of the part. An example of the latter is the case of turbine blade bosses or plug gauges which are plated with tungsten carbide. A plasma coating will give approximately one-half the life at one-fifth the price, but the cost of rebuilding an airplane engine or stopping an automated inspection line renders the cost of the coating inconsequential. Again, quality is the determining factor and plasma is not yet in a position to meet these stringent demands.

The selection range of coating materials and substrates is much less diverse for oxyacetylene than for plasma processing. The obtainable rms ground finishes are an indication of the porosity levels for both processes, however. It is also more difficult to keep the base from heating and still maintain an efficient operation, a factor of importance when selecting substrate material. Higher operating temperatures may cause thin sections and light pieces to deflect and distort.

Nickel and cobalt-base self-fluxing alloys can be subsequently torch or furnace fused by heating to a temperature between 1850° and 2200° F. where a eutectic is formed. The coating solidifies into a

⁶ Trademark of the Linde Corporation.

TABLE 2-III.—*Plasma Versus Oxyacetylene Metallizing*

Nickel..... (-200+325 Powder).	Plasma.....		0.008	0.003	A
	O ₂ -C ₂ H ₂	Wire Feed..... Powder Feed.....	0.011 0.007	0.001 0.001	D B
80% Nickel..... 20% Chrome. Prealloyed Powder.	Plasma.....		0.010	0.002	A
	O ₂ -C ₂ H ₂	Wire Feed..... Powder Feed.....	0.010 0.015	0.001 0.001	D B
Type 316 (18-8 Mo)..... Stainless.	Plasma.....		0.009	0.002	A
	O ₂ -C ₂ H ₂	Wire Feed..... Powder Feed.....	0.005 0.009	0.001 0.002	D D
Molybdenum.....	Plasma.....		0.007	0.0035	A
	O ₂ -C ₂ H ₂	Wire Feed..... Powder Feed.....	0.007 0.008	0.001 0.010	A A

Bend Test Rating: A—No Flaking, B—Good, C—Fair, D—Poor (0.060 in. thick substrate, 90° bend around 0.250 in. radius).

pore-free condition, metallurgically bonded to the base. The spray-and-fuse technique is being replaced on a limited scale by a transferred-arc plasma method which deposits and fuses the alloy in a single step. Conventional plasma-sprayed coatings have replaced fused hard facings in a few instances, but the processes are generally not considered competitive.

Metallic-arc hardsurfacing is a welding process and can be considered in the same classification as fused, self-fluxing alloys when compared to plasma coating. Disadvantages involve the facts that high local heating may cause distortion and that nonconductors and low melting point materials are not suitable as substrates. Deposits are usually applied in thick sections to heavy machinery rather than to precision pieces since welded parts are generally not subsequently ground to close tolerances. The deposits, however, usually contain some blow holes or pores.

The Rokide⁷ process is still the principal method for applying ceramic coatings although plasma coatings continue to be economically substituted in many applications. The primary limitation of the Rokide process is the necessity of obtaining the ceramic material in rod form. Investigations have been conducted to adapt these same ceramic rods to a plasma torch, but the published results have been inconclusive to date.

Table 2-IV gives an indication of the downward trend in cost as nitrogen and air plasmas are substituted for argon.

Table 2-V provides a comparison of the plasma arc with other spraying processes.

TABLE 2-IV.—*Operating Cost of Plasma Torch*

Gas	Flow	Gas Cost/ hr.	Elec./hr. (25 kw.)	Replace- ment Part/hr.	Total Hourly
<i>Present Plasma Torch</i>					
Nitrogen-----	100	\$2. 50	0. 63	0. 50	\$3. 63
Argon-----	60	5. 10	0. 63	0. 25	5. 98
Argon-----	100	8. 50	0. 63	0. 25	9. 38
<i>Proposed—N₂ Laminar, Air Acceleration</i>					
Nitrogen-----	5-10	0. 15-0. 30 Air 0. 03	0. 63	0. 50	\$1. 31-\$1. 46
<i>Air Plasma</i>					
Air-----	100	0. 01	0. 63	0. 75	\$1. 39

NOTES:

Electrical conversion efficiency—60 percent 1.5¢/kw.-hr.

Argon@8.5¢/ft.³—(Gas, prepurified dry).

Nitrogen @2.5¢/ft.³—(Gas, prepurified dry).

Air @1¢/100 ft.³.

⁷ Trademark of the Norton Company.

TABLE 2-V.—How Plasma Arc Compares With Other Spraying Processes

Process	Plasma Arc	Oxyacetylene Metallizing		Detonation ²	Metallic Arc and Gas Welding	Rockide ³
		Unfused	Fused ¹			
Choice of Coating Material.	Metal or ceramic that melts alloys, plastics.	Nonreactive metals; refractories with melting point <5,000° F.	"Self-Fluxing" alloys.	Tungsten Carbide with selected matrices, selected oxides.	Ferrous and cobalt base alloys; tungsten carbide-alloy, hard facing alloys.	Selected ceramics, Al ₂ O ₃ , ZrO ₂ , Co ₃ O ₄ , ZrSiO ₄ .
Choice of Base Material.	Almost all metals and ceramics; some organic materials.	Almost all metals and ceramics.	Metals with melting point >2,000° F.	Almost all metals and ceramics.	Weldable materials, usually ferrous base.	Most metals and some nonmetals.
Normal Processing Temp., F.	Usually less than 250° F.; up to 400° F. for a few coatings.	500-600	1,850-2,150	<400	Locally from 1,800° F. up to melting point of base.	4-650° F.
Type of Bond.	Mechanical	Mechanical	Metallurgical	Intimate	Metallurgical	Mechanical.
Dimensional Limits on Base. ⁴	0.005 in. dia. min., no max. limit.	0.030 in. dia. min., no max. limit.	0.069 in. dia. min., no max. limit.	Mechanical. 0.2 in. dia. min. to 60 in. max. dia.	Very small to very large.	Approx. 0.010 in. dia., no max. limit.
Coating thickness and tolerances, in. ⁵	0.002-0.1, ±0.001.	0.005-0.2, ±0.003.	0.005-0.2, ±0.005.	0.001-0.012 ±0.001.	0.1-0.5, variable	0.002 ± 0.001.

TABLE 2-V.—How Plasma Arc Compares With Other Spraying Processes—Continued

Process	Plasma Arc	Oxyacetylene Metallizing		Detonation ²	Metallic Arc and Gas Welding	Rockide ³
		Unfused	Fused ¹			
Surface Fin, rms micro-inch As Applied. After Grinding	75-125	150-300	150-300	125	Irregular	200-300.
	10 typically, as low as 2-4.	16-32	<5	As low as 1	Low as 5; often marred by blowholes.	<5 10-16.

¹ As sprayed coating is heated to melting point to consolidate coating and produce metallurgical alloying of coating with base.

² Flame-Plating.

³ Trademark of Norton Company.

⁴ These are practical limits; in some cases special techniques permit application of coating to thinner sections.

⁵ These are common values; limits often vary with base and coating materials.

Process advantages of plasma-arc spraying can be classified in the following five categories:

1. Generation of high temperatures far beyond the melting point of any known material; thus, consideration can be given to any material which has a discrete melting point or softening range.
2. Minimum contamination from the inert gas stream when spraying in the atmosphere, especially important for reactive metals and compounds. Since energy is derived from an electric arc, controlled-environment or reduced-atmosphere coatings are possible.
3. Maximum density and bond strength of coat compared to other commercially available processes because high gas velocities accelerate particles rapidly.
4. Minimum of substrate heating (less than 250° F.) even at close torch-to-work distance. Cooling air can be employed to deflect the hot plasma gas while high-momentum particles are projected onto the base.
5. Flexibility—mixing of powders, gradated or multilayered coatings applied to a diverse range of substrates including metals, ceramics, plastics, graphite, glass, and wood.

Limitations of the plasma process and equipment have inhibited its widespread use and should be considered here. The initial cost of equipment has been a limiting factor since the price of a plasma system consisting of torch, console, and power supply (less powder hopper) has averaged from \$5,000 to \$7,500 compared with \$1,500 to \$2,500 for equivalent oxyacetylene apparatus. Water cooling and arc length dictate minimum size requirements and prevent the use of extensions for coating inside diameters of 3 inches and less. Small internal diameters must be coated at an angle (not less than 45°), at which point coating quality is severely impaired.

The statement that the plasma torch can spray all materials which do not sublime or vaporize may be misleading since the dwell time within the hot plasma core is extremely short—a matter of micro-seconds. Only finely divided materials or those with attractive melting properties produce well-bonded, cohesive coatings. High specific heat and low thermal conductivity of the particles to be sprayed contribute to poor melting and deposition. While poor coatings are a consequence of inadequate particle melting, it is appropriate to point out that there are also cases where *excessive* heating is undesirable. Possible detrimental effects with cermets have been mentioned before. Furthermore, other materials, such as the pure carbides of tungsten

and boron, produce coatings with weak particle bonding due to the inability of the material to wet itself or because of loss of stoichiometry.

There are definitely some elements and compounds that can be eliminated from the class of sprayable material because they sublime, dissociate, or vaporize at temperatures very near their melting point. Included in this classification are many glasses, graphite, silicon, carbide, boron nitride, and silica. However, the assumption that any materials not in this category can be satisfactorily coated is unwarranted.

Since all commercial plasma torches presently employ powder feeds, it is essential that the material be obtainable in satisfactory form, preferably a dry, free-flowing powder in the size range between 15 and 44 microns. Rod feeds are advantageous because complete melting of the particle is assured; that is, the particle must be melted before it leaves the tip of the rod. Once the force of the accessory air stream exceeds the surface tension of the ceramic, the molten portion is torn away and atomized in a series of bursts. The air accelerates the particles and velocities as high as 600 ft./sec., or nearly twice the speed of a powder-fed plasma torch, are obtained. However, rods are more expensive and the availability of exotic materials in this form is limited. Moreover, it has been shown that complete melting of powders can be accomplished in a plasma torch under proper conditions.

Cermets and multicomponent powders should be presintered or prealloyed for best results. Blends should not be substituted in place of cermets as the deposit will not contain the same ratio of elements as the powder. A 60-percent nickel, 40-percent alumina blend injected into the plasma will normally deposit more nickel than alumina (approximately 75 percent nickel—25 percent aluminum oxide) as the ceramic will not be sufficiently melted. If the powder is then injected further upstream to lengthen the dwell time and melt the aluminum oxide, the nickel will begin to vaporize, and the deposited material will be unbalanced in favor of the aluminum oxide. A better approach is to use two ports positioned in the orifice to accommodate the melting properties of each material. The ratio of materials will remain intact, but homogeneous mixing will not occur. Another technique consists of ball milling the blend so that the two materials are in intimate contact with each other. However, the success of this approach will depend heavily upon the mutual affinity of the two materials, for if there is no wetting within the plasma, the result will be nearly the same as if there were no ball milling.

Materials formed by reduction processes are usually amorphous and agglomerated and require long dwell times in the plasma. As a result, very fine particles must be used or insufficient melting will occur.

Chromium and titanium borides, beryllia, thoria, and magnesia fall into this category. Subsequent calcining or high-firing will promote recrystallization and grain growth and improve coating deposition and density. Individual particles can be remelted to form spheres in a high-enthalpy, laminar plasma flame (Figure 2.15) to produce the same result. Spherical particles, free of voids and agglomerates, approach the true density of the material, and will deposit at up to twice the rate for the same power, gas flow, and carrier gas setting.

The next few sections will show that there are many variables which affect the rate of feed and efficiency of deposit. It is unrealistic to give specific figures without measuring the values against coating quality. There are methods for increasing deposit rates such as using multiple feed ports and larger diameter ports. Although there is an ample amount of heat in the jet, it is concentrated in a small volume which has been referred to as the core. It is interesting to note that the feed rate is nearly a straight-line function of density (except for some of the extremely difficult-to-melt materials). Therefore forcing excessive volumes of powder into the plasma flame will cause a portion of it to travel in the fringe of the gas stream and deposit as unmelted particles.

The powder hopper can have an adverse effect on deposit rate if the container is not pressurized to force the powder into the plasma core. A hopper vented to the atmosphere (as used with oxyacetylene torches) requires large quantities of carrier gas (20 to 30 cfh) to generate sufficient force to drive the powder into the jet core. The high volume of carrier gas has a quenching effect on the plasma in the region where the powder is melted, and all the particles may not be plasticized. Also, very low-density materials have a tendency to "float" on top of the flame. In such cases, the injection hole should be made smaller to increase the velocity of the carrier gas, thus imparting more momentum to drive the particles into the hot-core region of the flame. Figures 2.16A through 2.16D give an indication of the effect of various parameters on coating density. The peaks of the curves can shift or flatten out under certain conditions. In the case of Figure 2.16A, a coarser particle would shift the peak to the right and density would not drop off so fast at increased distance. Finer particles are accelerated to maximum speed in a very short distance and then decelerate rapidly, accounting for the sharp decline in density as the torch is moved away from the work. Thus, it is important to note that coarser powders will improve deposit rates and efficiencies, but will generally result in more porous coatings. However, when employing fine particles (less than 20 microns) the standoff is critical and should be maintained at approximately 2 inches. Published figures on deposit rates

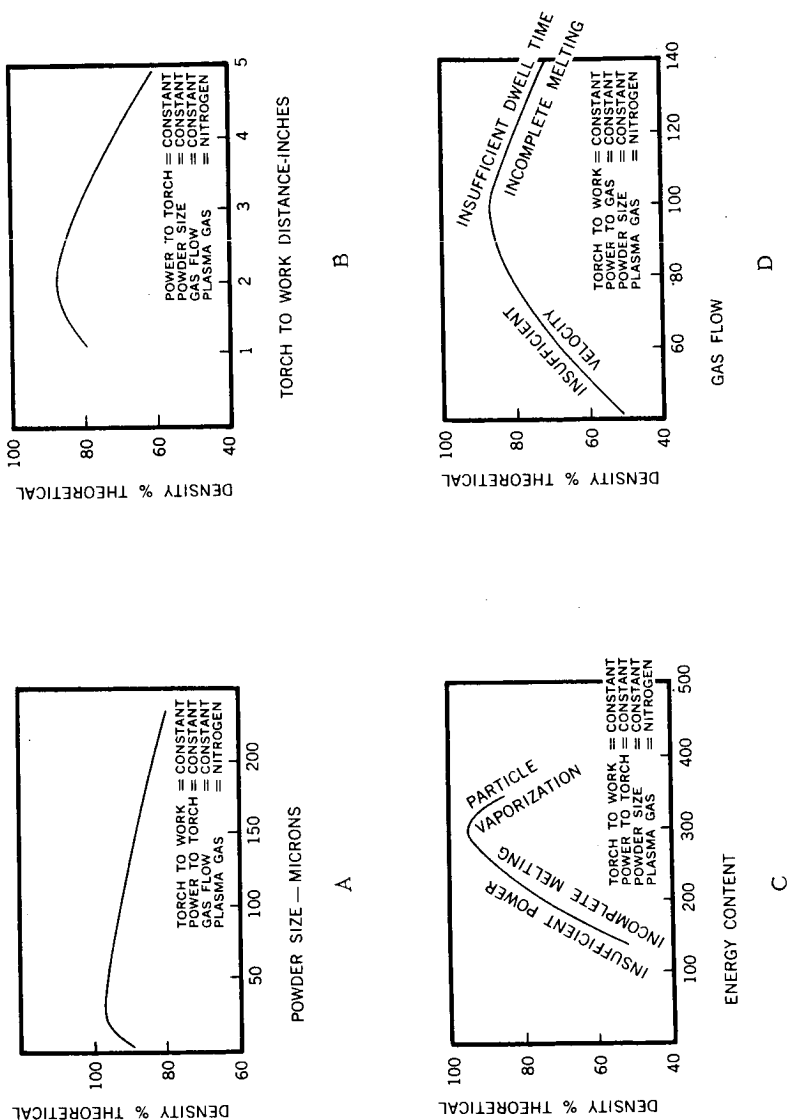


FIGURE 2.16.—Effect of powder size and torch parameters on density.
Courtesy of Thermal Dynamics Corporation

and efficiencies should not weigh too heavily with the user since best quality, high deposit rate, and efficiency are not obtained simultaneously.

Plasma environment is an important factor in the coating process. Once the powder has been selected, the material's basic properties of melting temperature, specific heat, and stability will determine the selection of plasma gas, flow, and power input. Sufficient thermal energy must be imparted to the particle to convert it from a solid to a semimolten state in a matter of microseconds. Much of the energy available from the gas will depend on the thermal conductivity of the gas. Although there is little information on the properties of gases at ionization temperatures, general use indicates that hydrogen provides the most heat with helium, air, nitrogen, and argon following, respectively. Argon is the simplest gas for electric arc use, but it is quite expensive and provides the least amount of heat. When spraying in the atmosphere where suitable, nitrogen will offer better melting and accordingly will produce better coatings. The small addition of hydrogen to either argon or nitrogen will raise the arc voltage and efficiency, increase the heat-transfer rate, and melt a given size powder at lower current. The addition of hydrogen will also provide a reducing atmosphere which is beneficial for spraying materials with a tendency to absorb oxygen. When spraying tungsten in a controlled atmosphere, the addition of 10 percent hydrogen gas has actually reduced the total amount of oxygen in the coating.

For spraying, the gas-sheath stabilized torch has advantages because all the gas is traveling longitudinally in a direction perpendicular to the substrate. In comparison, when operating with a vortex-stabilized arc employing small quantities of argon (40 to 60 cfh), the gas is traveling tangentially within the orifice, injection of the powder is more critical, and the spray pattern may be disturbed. Coating quality is impaired from lack of momentum although the relatively lower gas velocity promotes good melting.

The metals as a group are the simplest to spray because they exist as liquids over a fairly wide temperature range. The majority of them possess relatively low specific heats and are available as powder over a broad size range or in a narrow classification. This narrow classification allows optimum spray parameters to prevent underheating (low deposit efficiency) and overheating (partial vaporization of the "fines").

The oxides pose a greater problem since their melting temperatures and specific heats are generally higher. Factors which should be considered include ease of hydration, decomposition and sublimation points, and degree of reducing and nitriding tendencies. The carbides rarely occur in nature and hence must be prepared synthetically.

As a group they oxidize readily at high temperatures. Some decompose before melting while others will lose stoichiometry and form nitrides and oxides of different composition under certain conditions. The loss of stoichiometry when spraying carbides can be eliminated by using a carrier gas-enriched stream containing methane to produce a carbon-rich atmosphere. When not using an enriched carrier gas, it is advisable that argon or helium be used as the plasma gas in attempting to form a deposit of carbides with weak molecular bonds and strong nitriding or oxidizing tendencies. When sprayed deposits of borides, nitrides, and silicides are desired, their stability in a given plasma environment must be appraised in a similar manner.

Spraying environment beyond the plasma envelope is the final consideration in the spraying sequence.

At the present state of the art, most deposition is being conducted under ambient air conditions. Because high temperatures are produced by plasma flames, it is necessary to prevent excessive heating of both the base material and the deposited coating. Overheating can be controlled by :

1. Directing cooling gases onto the workpiece.
2. Increasing the torch-to-work distance.
3. Diverting the plasma flame from actual impingement on the substrate.
4. Insuring high gun-traverse rates.

Workpiece temperature must be maintained sufficiently low so that no warpage, oxidation, or loss of strength occurs. Uniform cooling is necessary so that cracking due to differential thermal stresses is avoided. It is also important that the coefficients of linear thermal expansion be known for the base material and the coating material. A thin coating of an intermediate expansion material may be desired to reduce stresses.

Technique and knowledge of the materials and parameters discussed in previous sections are the secrets of successful evaluation and use of the plasma system today. The torch can be described in its simplicity as a direct-current arc constricted within a tube. It is safe to state that a technician of average aptitude can learn to operate the equipment in less than an hour. The design of the equipment has been extraordinarily simplified, but the spraying of a material to produce a well-deposited coating is an art, requiring experience and highly developed technique. It has been unfortunate that many good applications of plasma coatings have been only cursorily investigated and subsequently rejected only because of poor coating technique.

PRESENT APPLICATIONS

The most important industrial uses for plasma flame-sprayed coatings at the present time fall into three main classes: (1) thermal barriers and refractories, (2) hard facings, and (3) conductors and dielectric materials.

The most extensively used plasma flame-sprayed coatings for refractory use are zirconia and tungsten. There have been very important recent developments in the spraying speed and deposit efficiency for zirconia so that it is now more economical to apply zirconia by plasma flame than by combustion-rod spraying. Specifically, commercially available equipment has recently been announced with spraying speeds of 10 lb./hr. with 75 percent deposit efficiency using 38 kilowatts with nitrogen-hydrogen mixtures. Plasma flame-sprayed zirconia coatings range from those with properties equal to rod coatings to coatings which are harder and denser than rod coatings.

Tungsten is used extensively as a refractory material for work at high temperatures. Recent developments in plasma flame-sprayed tungsten coatings have resulted in very high tensile and rupture strengths. In spraying fine grades of tungsten, tensile strengths of 11,000 to 12,500 psi with rupture strengths of 25,000 psi at a density 88 percent of the theoretical value have been attained. These developments involve the use of an argon flooding technique which blankets the area around the spray area with argon. However, the best coatings have been produced using nitrogen with a small percentage of hydrogen added as a plasma gas. An alternative technique has been developed which utilizes CO_2 for cooling the area immediately adjacent to the deposit area of the substrate.

Either technique permits the deposition of the tungsten under hot conditions with the gun close to the work, resulting in substantially increased physical properties. The flooding, or cooling, prevents oxidation and yields coatings comparable to those previously produced under ideal conditions in inert gas chambers.

The most important hard-facing sprayed coatings are the self-fusing type and the ordinary mixtures of carbides, such as tungsten carbide and chromium carbide, with matrix materials such as nichrome and the self-fluxing nickel-base alloys. Engine bearing applications tend to use chromium carbides with nichrome as a matrix, whereas, the general hard-facing applications (which require a hard finish) tend strongly toward the tungsten-carbide/nickel-base self-fluxing alloy mixtures.

Plasma flame-sprayed copper has better conductivity and general integrity than combustion-sprayed copper and is used in combination

with sprayed dielectric materials such as plasma flame-sprayed alumina for cryogenic elements.

The trend of applications for plasma flame spraying has been somewhat away from its use as a tool for producing self-supporting shapes and toward its use as a tool for producing permanent coatings in the above fields. It is expected that the spraying of other refractory materials, such as tantalum and columbium, will increase for special purposes and in some cases will compete with tungsten.

The hard-facing industrial uses have just begun and have hardly passed the test stage. However, the greatest growth in the next two years will probably be in this field. Extensive growth is also expected in the general electronic and in the cryogenic field but the future application in this field is not so clear.

Among the many uses of the plasma jet in the metals field are: repairing of blowholes in castings, rebuilding of mismachined surfaces, coating of ferrite parts, and hard-surfacing of nonferrous alloys. One group of researchers worked on the development of plasma-arc spray processes for the fabrication of free standing tungsten. This group was able to fabricate massive pieces of tungsten with wall thickness greater than one inch and weights in excess of 100 pounds. High-purity tungsten is currently being deposited in the exit cones of several solid rocket propellant systems. One particular item required for this field has generated a volume of spray work which is well over \$1,000,000 per year.

Plasma-arc deposited oxides are used for thermal, electrical, and wear-resistant coatings. The most commonly used materials are aluminum oxide and zirconium oxide. Although these materials can be deposited via oxygen-acetylene powder or rod-spray techniques, plasma-arc deposited coatings are quickly gaining favor because of deposit purity and increased bond strengths, as well as purely economic advantages. One applicator has shown that a zirconium oxide coating normally applied by oxyacetylene rod-spray techniques can be applied in considerably less time with plasma equipment which has been optimized for oxide depositions. Plasma flame-sprayed alumina is one of the best materials to meet the combination of requirements of good dielectric strength and reasonably good heat conductivity, and still have a cost in the range which permits its use for mass-produced industrial components.

Thermal and oxidation barriers are most commonly the refractory oxides which have high-temperature capability and low thermal conductivities. Refractory metals, such as tungsten, molybdenum, and tantalum, provide thermal protection at elevated temperatures in neutral or reducing atmospheres or when applied as undercoatings for

the more brittle oxides. Because of their brittle nature and low conductivity, the refractory coatings are subject to failure from thermal cycling or abrupt changes in temperatures (especially between 70° and 400° F.). The tendency of the coating to separate from the base is more pronounced when the substrate has high expansion characteristics. Separation of the coating due to thermal shock can often be remedied by a "spongy" or porous coating of refractory metal or other lower melting-point metals and alloys if environmental conditions permit. A more sophisticated technique of reducing thermal shock failure consists of applying a gradated coating by making a gradual transition from the base to the desired coating. It is preferable to keep the coating which is exposed to the hot temperature as thin as possible to minimize cracking. Gradation may be accomplished in a continuous or multilayered manner. However, the latter may be less desirable when failure is more likely to occur at the interface.

Graphite rocket nozzles are coated on the inside with tungsten. Generally a rhenium undercoating is employed to eliminate formation of a brittle interface caused by a graphite-tungsten reaction at high temperature. Tungsten provides excellent protection from high-temperature and high-pressure exhaust gases and maintains erosion of the throat within tolerable limits.

As oxidation barriers, sprayed coatings have not been so successful as some aluminide and beryllide diffusion coatings. Molybdenum disilicide has been the most promising of the sprayed coatings, but applications have been limited to laboratory investigations or single short-term exposures.

Cutting and shearing devices can employ wear-resistant coatings usefully, provided the coating is not used as a cutting edge. For example, circular saws can be coated with a wear-resistant material on the sides of the blade and can thereby eliminate cavitation below the cutting edge. Since the slight porosity of the coating substantially reduces the strength below that of the parent material, high point loading cannot be tolerated. Also, parts subjected to high impact loading, such as that encountered with plow blades or mining equipment, are now suitably protected by mechanically bonded plasma coatings.

Wear barriers offer the biggest potential to plasma utilization on a commercial basis. One field which has not been fully exploited in this regard is light metal hardfacing. A coating of tungsten carbide on aluminum, magnesium, or titanium is very tenacious and much more wear resistant than an anodized surface. Coatings of carbides

or oxides can be used to replace electroplated or nitrided surfaces or even inserts as means of obtaining hardened surfaces. They are most useful in minimizing metal-to-metal wear or providing compatible mating surfaces. Erosion from fine, high-velocity particles cannot generally be well resisted with plasma-sprayed materials since penetration into the pores weakens the coating. Also, cermets such as tungsten carbide/cobalt, consisting of a hard particle bonded in a softer metal, have a tendency to erode preferentially within the soft matrix and loosen the hard wear-resistant particles.

COATING MATERIALS

Powders introduced into the system produce a variety of spray patterns depending on the type of materials used, the powder feed rate, the plasma gas type and the flow, power, and nozzle configurations. In most applications it is desirable to obtain a fairly confined spray so that coatings can be applied to specific surfaces. To produce dense, well-bonded deposits, the plasma spray technologist, first of all, must possess a comprehensive understanding of the material he wishes to spray.

Table 2-VI lists the more popular materials being plasma sprayed today, although many others are under consideration.

Table 2-VII provides calculated maximum particle diameters and other parameters for a number of refractory materials.

Insufficient attention has been focused on the materials *per se* with regard to the various steps in the spraying process. The material selected for a given application should be based on all of its properties so the transition from powder to a successfully applied coating will be most effectively performed. From the standpoint of processing chronology it is logical to consider the material's behavior in distinct steps (Figure 2.17).

SPHEROIDIZING AND PARTICLE PREPARATION

The generation of small spherical particles has created varying degrees of interest in several areas, but with few exceptions it has been a laboratory curiosity. The first major shift to spherical powder occurred during the development of the solid-fuel propellants when the aluminum powder was specified in this shape. The high density, purity, and low resultant viscosity of the propellant mixture was enough justification to warrant the use of spherical powder even though the cost was four times greater than that for irregularly shaped powder.

TABLE 2-VI.—*Materials Which Can Be Plasma Sprayed*

Material	Approx. MP, °F.	Coating Properties of Interest	Specific Applications
Aluminum Oxide.	3,600	Reflector, insulator, chemically inert, high- strength ceramic.	Thermocouple sheathing, pump shafts and seals, turbine parts, subjected to heat and wear.
Chrome Oxide.	3,425	Stable in oxidation and reduction atmosphere.	Pick up backup rolls in chemical industry.
Chromium Carbide.	3,700	Wear resistant, low coef- ficient of friction. Most stable carbide in oxygen atmosphere.	Pump plungers, cams, arbors, valve stems, turbine blades.
Molybdenum.	4,750	Undercoating, good bond even on unprepared surfaces, antigalling.	Antigalling coatings on turbine blade buckets.
Molybdenum Disilicide.	3,700	Oxidation resistance, hard, tenacious coat- ing.	Refractory metal extru- sion dies.
Tungsten	6,200	Highest melting point metal, good hot strength, sprays easily, thermal shock resistant.	Free standing shapes, nozzles, crucibles, grid cages, nozzle throat liners.
Titanium Boride.	4,700	Very hard, stable, re- fractory resists molten metals, thermal shock resistant, and conduc- tor.	Secondary emission char- acteristics, nuclear ab- sorber, molten alumi- num nozzles.
Tungsten Carbide/ Cobalt.		Very hard, strongly ad- herent, wear and ero- sion resistance.	Skiving knives, gypsum saws, paper rolls and drums, feed and backup rolls, scrapers, alumi- num hardfacing.
Zirconium Oxide.	4,600	Low thermal conductiv- ity, high useful tem- perature, resists molten metals.	High-temperature extru- sion dies, rocket liners, electrical insulation, leading edges.
Zirconium Silicate.	3,000, Softens.	Low porosity, low ther- mal expansion, corro- sion or molten metal resistance.	Crucibles, metal pouring equipment, low-porosity corrosion.

TABLE 2-VII.—*Calculated Maximum Particle Diameters for Several Refractory Materials*

Material	Melting Point ° F.	Density (lb. _M /ft. ³)	Heat Capacity (Btu./lb. _M ° F.)	Thermal Conductivity (Btu./ft. ² /hr./° F./ft.)	Thermal Diffusivity (ft. ² /hr.)	Diameter (Max) (Microns)
Al ₂ O ₃ -----	3, 670	248	0. 30	2. 5	0. 034	47
ZrO ₂ -----	4, 890	349	. 16	1. 2	. 022	38
MgO-----	5, 170	223	. 25	3. 4	. 061	64
HfC-----	7, 030	761	. 07	20	. 375	158
TaC-----	7, 015	914	. 07	18	. 281	137
TiC-----	7, 000	308	. 22	10	. 148	. 99
ZrC-----	6, 405	420	. 12	12	. 238	126
W-----	6, 100	1, 204	. 04	10	. 208	117

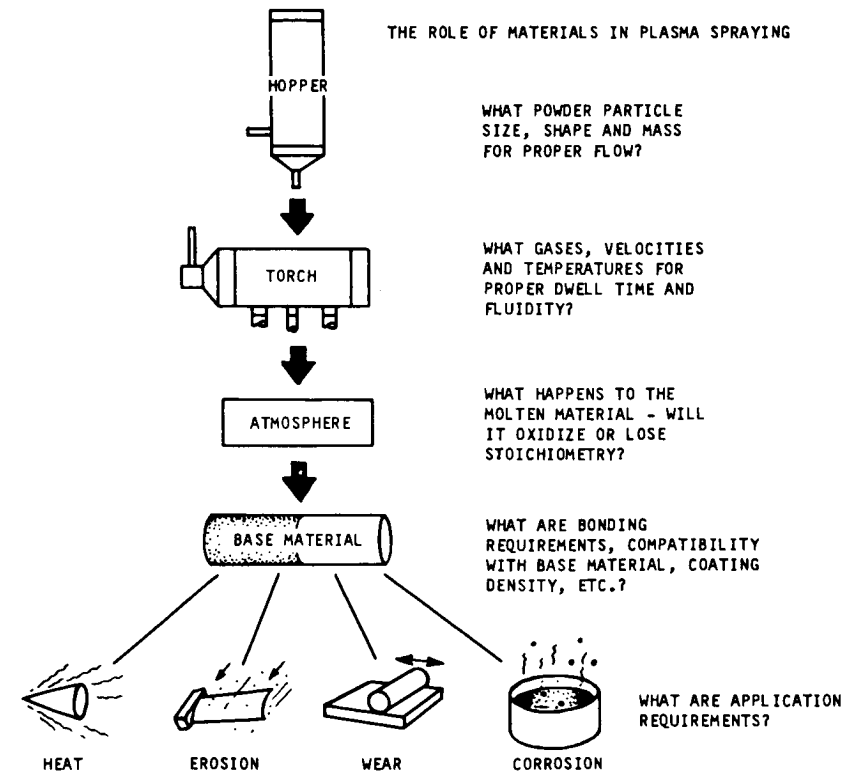


FIGURE 2.17.—Plasma spraying process sequence.
Courtesy of Thermal Dynamics Corporation

METHODS OF SPHEROIDIZING

Spheroidizing with nontransferred-arc devices involves utilization of presized particles formed by other techniques such as ball milling, attrition, and crushing. These particles are then passed through the hot plasma at a rate which is governed by the desired end product. With easy-to-spheroidize materials, normally of low melting point, a low-temperature plasma is used with a fairly large feed rate. With hard-to-spheroidize materials, such as the high-temperature carbides, extreme plasma temperatures are used along with low feed rates. In some cases it is desired only to round some of the sharp edges of particles. In this case, less heat is required.

Normal exposure times of particles in the plasma stream are less than 1/100 of a second. Thus, extreme heat fluxes are required. This involves temperatures far above the melting point of the material and in most cases temperatures far above the boiling point. Because of the extreme temperature differentials involved, the particles passing through a given size plasma stream of fixed temperature should be closely sized to minimize vaporization. Vaporization can come about since, if the temperature and residence time are adjusted to spheroidize the larger particles in a given feed material, the small particles become superheated and in many cases vaporized. It can be demonstrated that with improper sizing of material, as much as 20 percent of the feed material can be vaporized. This material, when vaporized, condenses into extremely fine particles in the 20 to 200 Angstrom unit range and condenses on various sections of the collection system. If the material is at all pyrophoric, the extreme surface area (100 to 1,000 m.²/g.) created by this vaporization makes the material extremely sensitive to handling. In addition to the problems of actually vaporizing substantial portions of feeds with wide particle-size distributions, additional feed problems can arise when using commercially available feeders.

The precision aspiration-type devices normally involve close spacing of components which allows the smaller particles to pass through, but not the larger ones in any widely distributed particle size range. For example, the larger particles hang up on the surfaces in the aspiration section, thus blocking the total feed area and causing feed rates to change during operation. Any variation in feed rate is directly reflected in the quality of the product, since the big particles dislodge large slugs of powder when they pass through, resulting in some material passing through the flame without being spheroidized. These problems can be overcome by closely classifying the powder and adjusting the flame conditions for each classification.

The simplest of spheroidizing systems utilizing the plasma technique can be characterized by extremely high-temperature and short-contact times as described previously. This, in turn, results in very low yields per kilowatt of electricity, much of the high-temperature energy being lost. This makes the simplified plasma spheroidizing system applicable to laboratory investigations where yield is not of interest or to materials in which the spheroidizing cost is a small part of the overall product.

To illustrate, a particular material can be examined with regard to this problem. Suppose the material actually required 0.12 kilowatt per pound to raise it from room temperature to its melting point, including the heat of fusion. This could be termed the theoretical spheroidizing yield if 100 percent of the input energy were utilized. If this material "X" is passed through a typical plasma stream with a velocity of 600 fps (feet per second) and a length of four inches, it has been determined that the best yield attainable is in the range of 1.2 kilowatts per pound. This indicates that the efficiency in this case was about 10 percent, i.e., 10 percent of the available energy was used in spheroidizing the material. Logical extension of this theory points out that longer residence times at lower average temperature would yield the same results and in addition produce higher efficiencies. This has been demonstrated in that the same material, when passed through a temperature zone of 3,000° F. by 10 feet long, produced an equivalent result with a power requirement of 0.5 kilowatt per pound. It should be pointed out at this time that the induction torch, in theory, holds more promise for this type of application because of the larger diameter and lower velocities of the plasma. As shown schematically in Figure 2.18, powder can be injected into the center of the plasma stream. This can be compared with side injection as shown in Figure 2.19 for the dc type of system. Side injection adds distribution problems and the necessity of using a carrier gas which dilutes the flame. In addition, these induction devices can be coupled in series to produce almost any length of heat source desired. Preheated gases can be utilized which in turn reduce plasma power-supply requirements. The induction device holds other basic advantages including operation on air for spheroidizing materials (such as ceramics) which can be handled in this atmosphere. Inert gases can be simply recycled without impurities affecting torch performance. For example, if some vaporizing occurs during the spheroidizing process with extremely fine powders, these powders can be recycled through the torch without affecting torch performance. If this were done with the dc plasma generator, the electrodes would deteriorate rapidly.

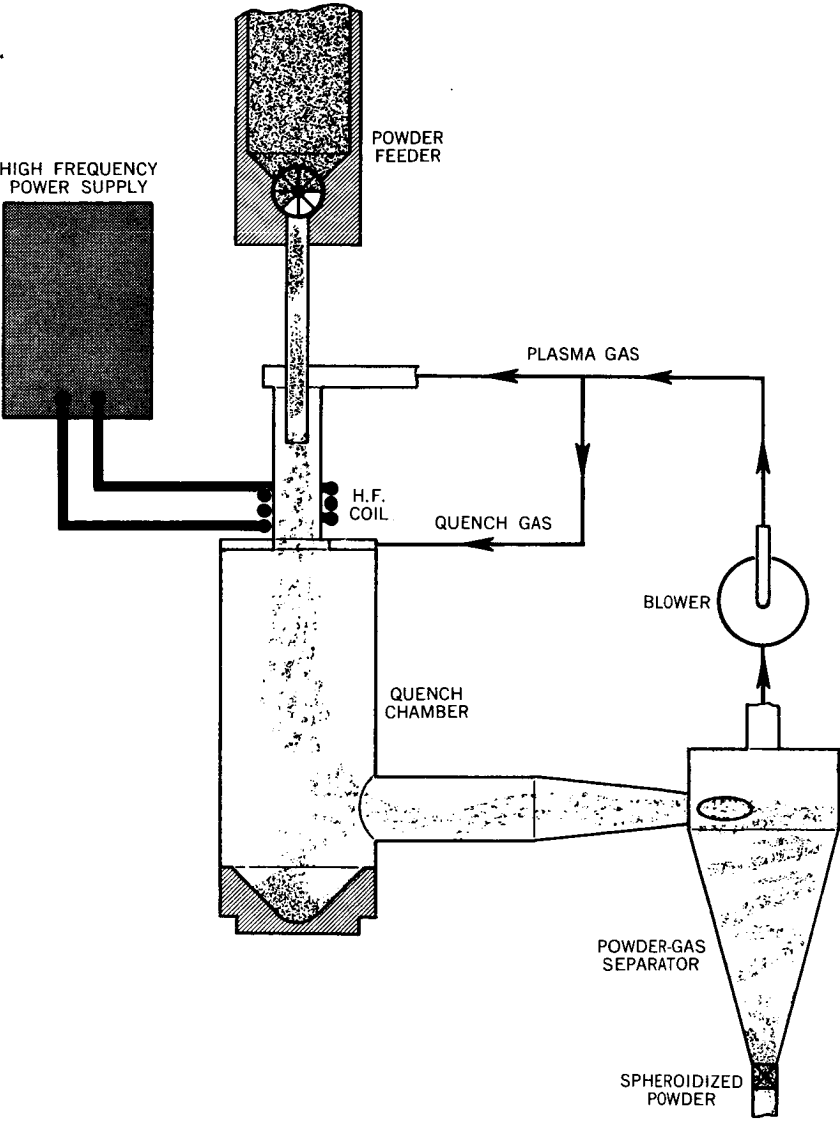


FIGURE 2.18.—High frequency plasma powder spheroidizing system.

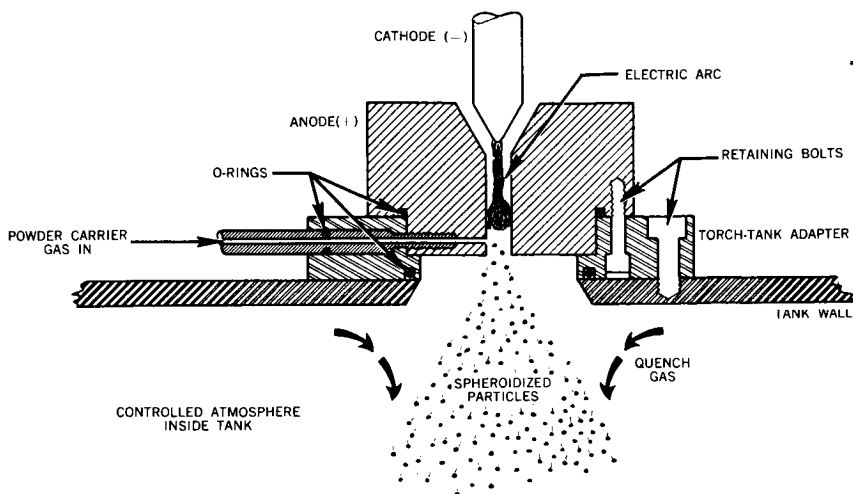


FIGURE 2.19.—Schematic showing dc plasma torch mounted to controlled atmosphere spheroidizing tank.

COSTS

Tables 2-VIII and 2-IX summarize costs of making powders by these various techniques. They include the necessary breakdown to give an overall picture of operating and consumable costs.

In summary then, plasma spheroidizing equipment, at the present state of the art, can be classified as experimental, inefficient, and directly applicable only to high-cost materials and those materials which heretofore have been impossible to spheroidize because of their high melting points. It is expected that the developments will now proceed in the area of lower temperatures and longer residence times of particles in the plasma to raise powder yields per kilowatt of power input. Overall spheroidizing plant costs utilizing present technology are also shown in Tables 2-VIII and 2-IX. In the case of spheroidizing high-temperature materials, the gases must leave the torch in the range of 5,000 to 7,000° F. unless used regeneratively. The energy contained in the gas at this temperature is extremely high and regenerative systems should be utilized where possible to minimize such losses. Spherical aluminum can be made by atomization techniques because of its low melting point. Plasma techniques cannot compete with atomization and are generally employed only for materials with melting points above 2,500° F.

Recently, there has been increased interest in spherical uranium ores for use as nuclear fuel elements. The high-enthalpy laminar plasma flame was a major technological breakthrough which widened the

TABLE 2-VIII.—*Cost of Transferred Arc and Production of Powder From Solid Stock by Plasma Atomization*

PROCESS COSTS USING TRANSFERRED ARC

1,000 Pounds per Hour Production Rate

ac Power 200 at \$0.007/kw-----	\$1. 75
Gas Argon (Recycle) Make-up 20%, 50 CFH at 5¢-----	2. 50
Total Process Cost per 1,000 Pounds-----	4. 25
Total Cost per Pound of Powder-----	0. 00425

COSTS RELATIVE TO PRODUCTION OF POWDER
FROM SOLID STOCK BY PLASMA ATOMIZATION

1,000 Pounds per Hour Capacity

Labor-----	\$100, 000
Plant Cost:	
Power Supply-----	\$5, 000
Control System and Torch-----	7, 000
Tank-----	10, 000
Feeding Mechanism-----	2, 000
Cooling and Recycling-----	10, 000
Building-----	100, 000
Powder Handling-----	50, 000
Furnace-----	50, 000
Contingency-----	50, 000
Total-----	284, 000
Plant Cost Amortized Over Five Years-----	56, 800
Gas and Electricity 4,500,000* lb./yr-----	19, 100
Total Cost To Produce 4,500,000 lb-----	175, 900
Cost per Pound-----	0. 0391

*300 days/yr. at 15 hr./day.

TABLE 2-IX.—*Costs of Powder Spheroidizing and Production of Powder*

PROCESS COSTS POWDER SPHEROIDIZING USING PLASMA FLAME

1,000 Pounds per Hour Production Rate

ac Power 1,200 kw. at \$0.007/kw-----	\$8. 40
Gas Argon, 500 CFH at 5¢-----	25. 00
Total Process Cost per 1,000 Pounds-----	33. 40
Total Cost per Pound of Powder-----	0. 03340

TABLE 2-IX.—*Costs of Powder Spheroidizing and Production of Powder—Continued*

COSTS RELATIVE TO PRODUCTION OF POWDER		
1,000 Pounds per Hour Capacity		
Labor		\$100, 000
Plant Cost:		
Power Supply	\$ 30, 000	
Control System and Torch	7, 000	
Tank	10, 000	
Feeding Mechanism	2, 000	
Cooling and Recycling	10, 000	
Building	100, 000	
Powder Handling	50, 000	
Furnace	50, 000	
Contingency	50, 000	
Total	309, 000	
Plant Cost Amortized Over Five Years		61, 800
Gas and Electricity 4,500,000* lb./yr.		156, 000
Total Cost to Produce 4,500,000 lb.		317, 800
Cost per Pound		0. 07

* 300 days/yr. at 15 hr./ day.

capability of the plasma torch to produce spherical uranium ore. In contrast to standard plasma flames used for spraying, the laminar flame is hotter, lower in velocity (longer dwell times of particle in flame), and noiseless; it can be up to 30 inches long. Feed rates of 20 to 30 lb./hr. of uranium carbide are not uncommon and place this dc plasma flame well in front of the plasma torch. The plasma torch is very limited in the amount of feed material which can be injected without extinguishing it. The major companies and government organizations in the nuclear field are using this technique for producing spherical particles.

Although the market for spherical-particle-producing systems is limited, it is great enough to warrant special system engineering by most manufacturers of plasma devices. With the amount of laboratory investigation being performed, it appears that other more important and higher volume applications will also be developed.

ADVANTAGES

Spherical particles have many desirable properties including the following:

1. Free flowing
2. High apparent density
3. Lowest possible surface area/volume ratio
4. High true density and purity
5. Controllable porosity mixtures
6. Capability of being closely screen-sized.

Materials which have been spheroidized for various purposes include the following:

<i>MATERIAL:</i>	<i>MAXIMUM MESH SIZE (100 percent Spheres)</i>
Alumina -----	60-80
Zirconia -----	60-80
Tungsten -----	50-60
Columbium -----	60-100
Beryllium -----	60
Boron Carbide -----	150-200
Zirconium -----	60-80
Zircalloy II -----	60-180
Uranium Dioxide -----	80-100
Uranium Carbide -----	100-120
Zirconium Diborate -----	120-120
Mullite -----	60-80
Tantalum -----	60-80
Stainless Steel -----	50-60

In addition to using a nontransferred laminar plasma flame, spherical particles can also be produced by melting a rod with the transferred arc. This process is capable of extremely high feed rates, but it is more difficult to control particle size.⁸

It is apparent that the future of spheroidizing will depend on the development of processes requiring the unique properties of minute spheres.

POWDER MANUFACTURE

A manufacturing process, utilizing the high-intensity arc vaporization techniques for the production of submicron-size powders, has been investigated by the Vitro Laboratories Corporation, West Orange, New Jersey.⁹ This extensive program demonstrated that a high intensity arc process is feasible for the production of particles less than 0.1 micron in size with purities exceeding 99 weight percent.

The high intensity arc process developed by Vitro differs from the conventional plasma jet devices in that a consumable electrode is used to feed the reactants into the plasma zone, and the electrode in itself serves as the anode in the plasma circuit. Essentially the process is one of arc vaporization, and temperatures in excess of 7,000° F. have been obtained.

As the vaporized material leaves the reaction chamber in the form of a plasma or tail flame, rapid condensation occurs. The cooling rate can be controlled in such a way that the extremely fine state of subdivision characteristic of the plasma flame can be maintained.

⁸ The Linde Corporation makes commercial products by this technique.

⁹ Holmgren, J. D., et al.: "Development of Submicron Powder Manufacturing Method," Final Technical Engineering Report, ASD TR 62-7-884, Vitro Laboratories Corporation, AF33(600)-42916 (August 1962).

With rapid cooling, particle growth can be inhibited with a high degree of flexibility.

Materials for which data are available include silica, alumina, thoria, tungsten oxide, molybdenum oxide, magnesium oxide, zirconium oxide, iron oxide, titanium oxide, columbium oxide, tantalum carbide, tungsten carbide, aluminum metal, titanium metal, columbium metal, tungsten metal, and molybdenum metal. Tentative processes have been established on a pilot basis for most of these materials. According to the investigators, the processes which were developed can be further scaled up and appear to be economically attractive.

CHEMICAL SYNTHESIS

Most of the chemical investigations in the country have been conducted under company secrecy; therefore, it is difficult to estimate the actual success with which the plasma generator system has been applied to the synthesis of chemicals.

It is known that several companies are investigating the practicality of commercial ventures in this area. Noteworthy contributions to the state-of-the-art are being made by many research groups throughout the world.

In the absence of production data the information presented in this section is necessarily limited to research results. Early in 1963, the National Aeronautics and Space Administration funded an investigation of the state-of-the-art. Two reports resulting from this effort are reproduced in their entirety herein (ref. 66). Certain developments occurring in recent months have been added where pertinent.

A development during 1963 which merits special mention was the announcement by the DuPont Company that commercial production of acetylene is used in the production of neoprene. Further details have not become available.

The applications of plasma technology to this field date back to the early 1900's when plasma generating devices were first being considered for chemical synthesis. Of the early designs, that of Professor Shonherr was of most interest. He stabilized an arc through a long tube and developed it to the point where, in 1928, arc reactors for producing acetylene from natural gas were placed in operation at Huls, Germany. These units operated at 8,300 volts and 850 amperes for a total input of 7 megawatts. Enthalpy levels were very low because the goal was to maximize the production of acetylene.

The use of modern plasma devices in the chemical field has been retarded considerably by the secrecy dictated for competitive reasons. In many cases, research is being conducted in laboratories using equip-

ment designed for other purposes. It is often difficult to determine just what operating parameters the chemist needs. There is no question that both the equipment manufacturer and user are hampered by company security requirements.

The interest in the chemical field has risen sharply during the past year and production processes in the near future seem likely. Power levels will in all probability be much higher than the 50-kw. units which are now used for experimentation. One difficulty with which the equipment manufacturer must cope concerns the long duty cycles required for continuous processes. In contrast to materials testing, where the test time generally is 1 to 3 minutes, it will almost certainly be required that a single set of electrodes run for one week minimum. The problem of running for lengthy periods will be more readily solvable when the operating parameters are defined.

So far, activity has centered around the heating of hydrocarbons (such as methane and propane) to some temperature above $2,000^{\circ}\text{C}$. at which acetylene forms through a rapid heating and quench. Typical yields of acetylene, when hydrocarbon stock is injected into a $3,000^{\circ}\text{F}$. gas stream, are in the range of 6 percent; when the stock is injected into a $5,000^{\circ}\text{F}$. gas stream, yields are in the range of 9 percent. It has been demonstrated that gaseous hydrocarbon stock when injected into an $8,000^{\circ}\text{F}$. nitrogen plasma results in an off-gas yield near 18 percent by volume. These yields are to be compared with a theoretical yield of about 26 percent for such a reaction. There were 3 to 4 kilowatt hours involved per pound of acetylene generated in the latter case. These yields are encouraging. This is to be compared with production processes now commercially used which require in the range of 2 kilowatt hours per pound.

The lead time involved in getting any chemical synthesis program on stream is probably the longest of any plasma application area. A number of years may yet pass before many processes are refined to commercial significance.

The high-intensity arc, as discussed previously, involves vaporization of the anode stock. It is understood that a few industrial pilot plants producing materials by this technique are currently in existence. One plant is fabricating a vaporizable anode of silica and carbon with appropriate pitch binder. Vaporization is conducted in an oxidizing atmosphere. Most of the carbon is burned and the remaining vaporized silica condenses into extremely fine particles in the 200 Angstrom unit range. The product is used in many of the same applications as carbon black, and also as an extender of paints. It is understood that present operating costs of such a technique are similar to those of commercial silica production by a process starting with silicon tetrachloride. It is expected that this process will remain in

the development stage until a breakthrough is achieved in which costs are reduced, or a unique product is demonstrated.

It is believed that other applications of the high-intensity arc center around production of carbides utilizing materials such as uranium. It would seem that the high-intensity arc process, where applicable, would require minimum power because most of the electrical power input would go directly into vaporizing the material. The disadvantage of this process would seem to be one of little control, i.e., either the material must be vaporizable in the product contemplated or the process is not applicable. This is not the case with more standard plasma generators where temperature can be controlled over wide ranges, and the product is little affected by heat.

CARBON BLACK FORMATION

Hydrocarbon stock can be injected into the plasma and carbon black thereby formed. Conventional techniques presently utilize an air-fuel, gas-turbine-type combustor. The hydrocarbon stock to be cracked is injected into the center of the combustor. The old channel techniques, which use a pooled channel in a gas-diffusion flame, are also used conventionally. The carbon black, which forms in the diffusion flame and deposits on the cold surface of the channel, is continually removed by some type of automatic scraping mechanism. Plasma holds the promise of creating a differently shaped particle or a particle with different surface conditions.

Carbon blacks are used as fillers in plastics and rubbers, and as a base for some inks. Compounding of rubber for automobile tires requires as much as 40 percent carbon black by weight. In this application the binding properties of the carbon black particle to the rubber are all-important. In addition, the end product often has different abrasion and internal heat-generation characteristics which depend on the particle size, shape, and method of manufacture. It is understood that the surface condition of the carbon black particle is also important for proper bonding to the rubber. Some contained oxygen should be present to promote active bonding. Particles made without this free oxygen on the surface produce only a mechanical bond and a poor grade of rubber results. It is believed that plasma may produce some unusual effects with regard to the above properties. Although investigations are continuing, the point has not been reached where any commercialization has resulted.

ORE REDUCTION

Much speculation and some experimentation have been devoted to fast reduction of ores at high temperatures. If successful, a high-temperature reduction plant could reduce the capital investment con-

siderably and at the same time achieve an order of magnitude increase in production rate. For example, tungsten oxide is now reduced in a hydrogen atmosphere at around 900° C. One process requires hours of exposure time with the powder being placed in small boats which are drawn through the hydrogen furnace on a chain conveyor. If the tungsten oxide were to be passed through a hydrogen plasma and made molten, the reduction might well take place in less than a second. This has been demonstrated with cesium oxide. In this case a reducing atmosphere is not necessary since decomposition occurs in the hot plasma stream.

The basic problem inherent in all such schemes is the containment of the hot material and the efficient reclamation of the large amount of heat in the materials leaving the reduction zone. It is the opinion of some workers in the field that work along these lines is continuing in a number of research laboratories throughout the country. However, no refinement to actual practice has yet resulted.

LABORATORY EQUIPMENT

Essentially, the plasma equipment commercially available consists of torches and the accessories for their control. The torches must be coupled to reactors and quenching devices to be useful in chemical processing. In view of the fact that complete plasma systems for chemical synthesis are not available commercially, some generalization about the equipment that has been used in laboratory experiments may be helpful in illustrating how plasma generators are used to bring about reactions.

Consumable graphite cathodes have been used extensively in experiments in which carbon was to be a reactant. Leutner (67) used carbon vaporized from the graphite cathode to synthesize cyanogen. Grosse, Leutner, and Stokes (68) also used consumable graphite cathodes in their preparation of hydrogen cyanide. Cathodes that serve as a source of reactants simplify the equipment required for experimental purposes and give control over the purity of carbon, but they introduce the problem of maintaining a constant distance between electrodes. The introduction of carbon as a fluidized powder or as a constituent of a gas would appear to be more desirable in commercial installations. It should be noted, however, that some processes may be dependent upon consumable electrode techniques; for example, the method for producing uranium carbide by the reduction of uranium oxide, as described by Gibson and Weidman (69).

Tungsten or 2 percent thoriated-tungsten cathodes have been most frequently used in experimental work when this electrode has been intended to be nonconsumable. These are usually designed so that they can be water-cooled.

Copper water-cooled anodes have been commonly used in experimental work. When nitrogen is used as the plasma gas, some investigators have used tungsten or graphite inserts in the copper anode to protect it from melting. When noble gases are used, this precaution is not necessary. Figure 2.20 shows two reactors suggested by the Thermal Dynamics Corporation. Both are based on the transferred-arc plasma jet. One uses a water-cooled anode and the other uses a consumable aluminum anode.

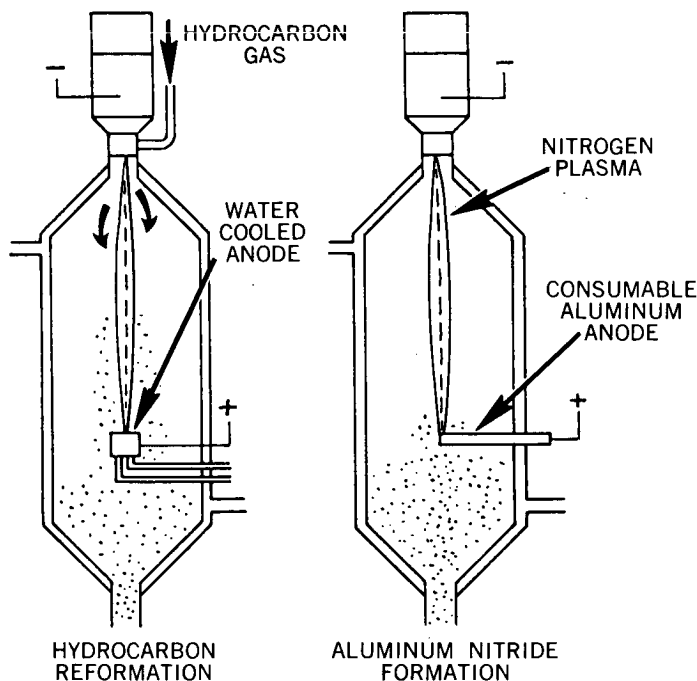


FIGURE 2.20.—Reactor schemes for two thermochemical reactions, using transferred-arc plasma jets.

Courtesy of Thermal Dynamics Corporation

The reactor chamber may be of any configuration required to accommodate feed material, quenching, and recycling. Stokes and Knipe (70), in their research on the preparation of nitrogen-containing compounds, used a plasma generator, powered by a 600-ampere welder, with a $\frac{1}{8}$ -in., 2-percent thoriated-tungsten cathode and the copper anode with a pure tungsten insert. The anode and cathode, which were separated by a $\frac{1}{4}$ -in. Teflon gasket, and the reaction chamber were water-cooled. Nitrogen, the plasma gas, was fed through an annular gas manifold and its flow measured by a flow-

meter. Gases or fluidized solids were injected into the plasma from a ring attached to the bottom of the plasma generator.

The chamber had a fitting through which variously shaped "cold fingers" could be inserted. For collecting solids, the cold finger was set close to the feed ring to quench the products. Such devices were also used to quench the reaction when gaseous compounds were formed. When gaseous compounds were prepared, freezeout traps were used, with either dry ice or liquid nitrogen as the coolant. In all cases, a positive pressure was maintained on the systems to prevent the entry of air. A diagram of the system is shown in Figure 2.21.

Modifications of this equipment are described by Grosse, Leutner, and Stokes (68). Their report also gives details on feeding devices and methods for quenching and collecting samples.

In general, the methods for quenching reactions and collecting samples, separating reaction products, and recycling to conserve energy and make use of byproducts are the conventional processes of chemical engineering and must be worked out for each reaction. The literature to date gives only meager information about devices or processes that would be incorporated in a system downstream from the flame nozzle—for the reason that there have been no commercial installations and only a few laboratory experiments to report. It is known, however, that studies are currently in progress on quenching methods and downstream systems, and some of these undoubtedly will be reported in the literature in the near future.

Proposed reactor schemes for the production of acetylene, cyanogen, and carbon black are shown in Figures 2.22, 2.23, and 2.24.

THE PLASMA JET IN CHEMICAL PROCESSING

Development of practical procedures for raising the temperatures of gases to as high as $50,000^{\circ}\text{K}$. and maintaining such temperatures indefinitely under relatively precise control opens up new vistas in chemical processing. Although relatively few studies have been conducted on the use of the plasma jet in chemical technology, there is ample evidence to suggest that plasma chemistry could have important industrial connotations. It could be used in an era when the reactions that normally take place only in or on the stars have practical industrial application.

One must approach the subject cautiously, however, since the state-of-the-art has hardly progressed beyond the speculative stage. The research that has been done is intellectually stimulating, but not technically and economically definitive. Nevertheless, those who have worked in plasma chemistry express themselves confidently on the potential for industrial as well as scientific benefits.

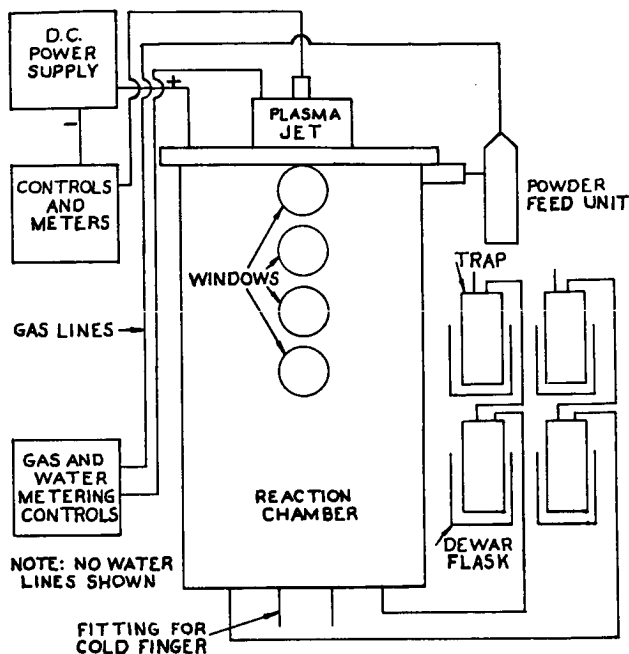


FIGURE 2.21.—Diagram of system for two thermochemical reactions, using transferred-arc plasma jets.

Courtesy of Thermal Dynamics Corporation

Marynowski, R. C. Phillips, J. R. Phillips, and Hiester, in the introduction of their paper on the thermodynamics of systems applicable to plasma-jet synthesis, state that "even the predominantly qualitative and empirical research on plasma chemistry to date indicates that this new technology has significant potential."

Industrial and Engineering Chemistry, in a staff-written article on "Plasma—Fourth State of Matter" (72), terms the ability to fix equilibria at ultrahigh temperatures a "new technique with fantastic possibilities." The article concludes with the statement that the "industrial applications of many of the chemical syntheses seem not too remote. Cost calculations based on scaled-up research installations have shown estimates of cost not more than double the current market price for acetylene and hydrocyanic acid, and even lower for cyanogen. At this early stage, the figures look encouraging. The plasma jet should prove to be a versatile process tool as well as a valuable aid to increasing knowledge of matter."

Reed (73), in summarizing the potential uses for the plasma torch, comments as follows: "The complete vaporization and dissociation of molecules can also be used to produce new compounds and study chemi-

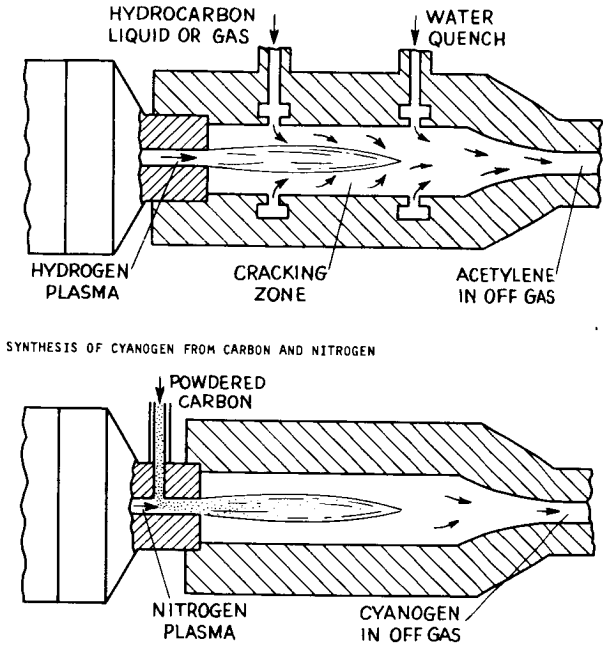


FIGURE 2.22.—Plasma reactor schemes for the production of acetylene and cyanogen.
Courtesy of Thermal Dynamics Corporation

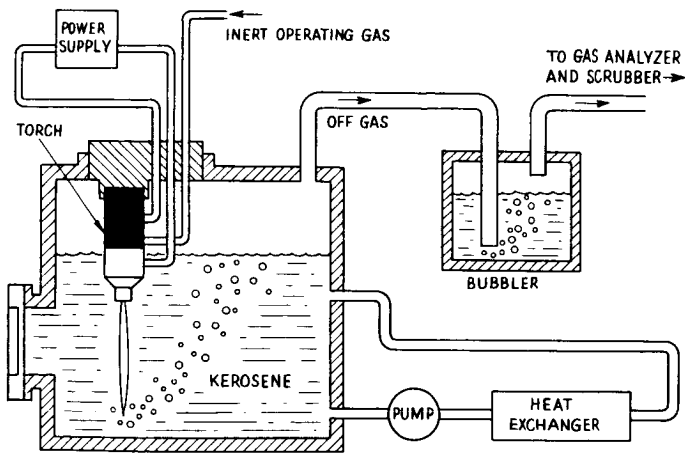


FIGURE 2.23.—A plasma method for the production of acetylene from liquid hydrocarbons.
Courtesy of Thermal Dynamics Corporation

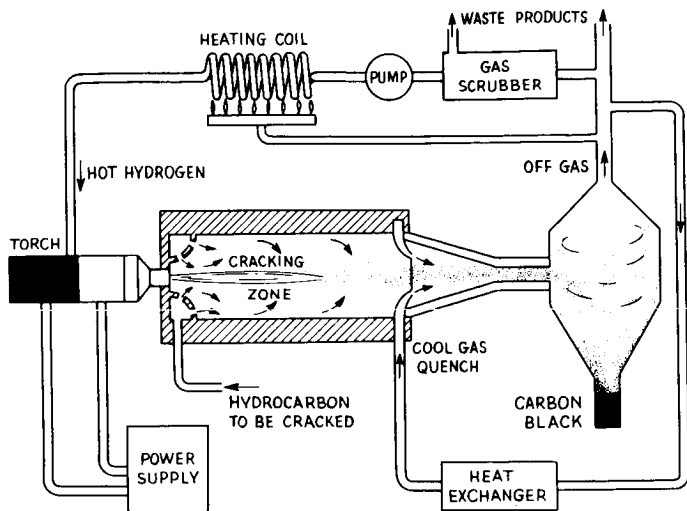


FIGURE 2.24.—The Thermal Dynamics Corporation's proposed scheme for cracking hydrocarbons to produce carbon black.

Courtesy of Thermal Dynamics Corporation

cal reactions at very high temperatures. Chemicals such as acetylene have been produced in very high yields in the dc plasma torches . . ."

Industrial and Engineering Chemistry, in a subhead to an article on "Producing Acetylene in a Plasma Jet," tells its readers "Keep your eye on plasma-jet processing. With lower power costs, this method could become economical for many reactions, such as: manufacturing hydrogen cyanide . . . acetylene . . . cyanogen; reduction of metal oxides to powders; fixation of nitrogen; preparing metal nitrides; preparing thiophosphonitrilic compounds."

Anderson and Case (74) introduce their paper on "An Analytical Approach to Plasma-Torch Chemistry" with the statement: "Within the last six years there has been a strong interest in plasma-torch chemistry. The plasma torch has stimulated the study of high-temperature chemical reactions because of its potential as a research tool and its potential as a production unit. Possible applications for plasma-torch chemistry are the decomposition of compounds to form the elements, the formation of endothermic compounds (either via a decomposition route or by a direct synthesis from the elements), and the formation of free radicals to be used as intermediates in subsequent reactions."

Baddour and Twasyk (75) regard differentials in cost increase in processing factors as favoring the economics of high-temperature reactions. They state that "on a long-range basis, commercial processes involving very high temperatures should become more com-

petitive since the cost of electric power has remained relatively stable while material and labor costs have generally been increasing rapidly."

Thorpe (70) lists the anticipated chemical applications for the plasma jet as: reforming of hydrocarbons; reduction processes; free radical formation and capture; fine-fiber production; crystal growing; and heat sources for recycled gases in other chemical processes, such as fluidized beds.

PLASMA CHEMISTRY

Plasma chemistry is quite different from ordinary chemistry, which, for both technical and economic reasons, becomes infeasible at about $3,000^{\circ}$ K. At temperatures above $5,000^{\circ}$ K., unusual things begin to happen. No solids exist at atmospheric pressure, and ions and electrons—rather than molecules—become the common species. All particles, even those without electrical charge, have great kinetic energy. Under such conditions, highly excited atoms may react to give compounds that are not likely to be formed at lower temperatures. Some of these may be "unearthly" in nature—combinations and forms that have possibly continuous existence in the favorable equilibria of stellar bodies or atmospheres, but are only transient under ambient conditions on earth.

There is no precise definition of plasma chemistry. In general, plasma-type reactions begin to occur when temperatures reach the range of $3,000$ to $6,000^{\circ}$ K., where diatomic molecules, such as hydrogen and nitrogen, have enough energy to break their chemical bonds. Reed (73), in explaining the mechanism of plasma reactions, starts with the low-pressure plasma, such as is found in the fluorescent light. In plasmas at 10^{-3} atmosphere, positive-charged ions and negative-charged electrons exist and are accelerated in opposite directions by the applied field. Collisions are relatively rare, because of the sparsity of particles at these pressures; an individual electron travels a considerable distance between collisions. When it finally collides with an atom, it has gained enough energy from the electric field to produce an ion by knocking off an electron—or at least to excite the atom and cause it to emit light. Low-pressure plasmas make excellent light sources since most of the energy is used for making light rather than heat.

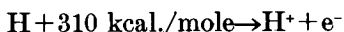
At one atmosphere of pressure, however, the mean free path of the electron between collisions is a thousand times smaller, and there are a thousand more collisions per atom per second. Although the amount of kinetic-energy transfer between electrons and atoms is still small per collision, there are enough collisions to distribute the energy uniformly among the electrons, atoms, and ions. A thermal equilibrium is established, and the language for thermodynamics, rather

than atomistic language, becomes appropriate for discussing heat and mass flow and the energy-temperature relationships within the plasma. Another consequence of the equilibrium is that temperatures beyond those of chemical flames are established.

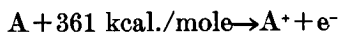
Reed uses energy-temperature relationships in a gas to differentiate high-temperature behavior. As one adds energy to a gas, the temperature rises proportionally as long as all the energy is used only to heat the molecules. There is no dissociation, much less ionization, and the thermal energy increases linearly with temperature. As temperatures approach the range of 3,000° to 6,000° K., however, diatomic molecules are no longer stable. In the case of hydrogen, the reaction.



occurs. Here, about seven times as much energy is necessary to carry the gas through the dissociation range as is needed to reach it. Further energy input causes the dissociated atoms to ionize, following the equation

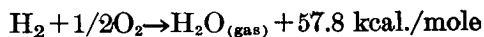


Monatomic gases, such as argon, ionize directly at a somewhat higher temperature. In the case of argon, the reaction is



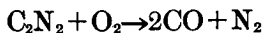
with the minimum plasma temperature being about 10,000° K.

These considerations, Reed points out, help us understand the limit that nature sets on flame temperatures. For example, an oxyhydrogen flame derives its energy from the formation of molecules of water, thus:



The temperature of such a flame, resulting as it does from the heat liberated in the formation of water, cannot correspond to a high degree of molecular dissociation of water.

The oxycyanogen flame



has the highest known flame temperature, 4,850° K., for any common gas. This is because CO and N₂ are extremely stable molecules. N₂ has a dissociation energy of 225 kcal./mole and CO, 257. The hottest flames, thus, are those in which combustion products are very stable—have high dissociation temperature.

Temperatures found in thermal plasmas are not so limited. Their temperatures tend to lie at that point where from 10 to 50 percent of the atoms are ionized. Ionization beyond 50 percent is counteracted by thermal expansion of the gas, which means that conductivity, and thus temperature, reaches a limiting value. Resulting temperatures are thus four to five times maximum flame temperatures.

When the plasma jet is used as a high-temperature source to bring about chemical reactions, two steps are involved: the first is the decomposition of the molecules either of the reactive plasma gas, or of a gas fed into the plasma, into atoms, or into activated atoms; the second is the freezing out of the chemical equilibria attained by fast-quenching methods.

In general, two different types of chemical reactions may be carried out using plasma-jet temperatures. Compounds may be decomposed into their elements or into more stable compounds. Exothermic reactions are unpromising because the chemical equilibrium at the higher temperature is less favorable for the compound than for its elements. If an exothermic reaction is represented thus:



it can be seen that the heat content of the plasma would tend to suppress the reaction and shift the equilibrium to the left.

Endothermic reactions, however, are favored:



There is enough heat to supply the endothermic need and force the equilibrium to the right, and, as AB is withdrawn, the reaction continues.

In addition to compounds, free radicals—to be used as intermediates in subsequent reactions—may be “frozen” out of the equilibria.

There are various methods of using the plasma jet to bring about reactions. The hot gas stream may be a reactant in itself, or it may serve merely as a heat source. Various reactions have been studied, using hydrogen and nitrogen as reactive plasma gases. Argon and helium are usually used when the plasma gas is to act as a heat source only—in such instances to heat an injected gas or vaporized solid reactants. Reactants that are solid at normal temperatures may be introduced into the gas stream by incorporation into consumable electrodes. They enter the plasma flame as gases where they may react among themselves, with the plasma gas, or with an introduced reactive gas. The possibility of feeding fluidized solids or aerosols of liquids (made with either a reactive or inert gas) into the stream

has also been investigated. Damon and White (77) suggest feeding finely ground phosphate rock downstream from the arc in a proposed process for making phosphorus.

The equilibria attained in the plasma reactor can be favorable for the formation of end products, such as acetylene or hydrogen cyanide, that are stable at room temperature. Usually, however, the species that are stable or metastable at plasma-jet conditions are unstable outside the reactor. Among such species are ions, excited and unexcited atoms, and radicals. Thus, in the majority of cases, the production of desirable end products involves more than merely trapping the species produced in the plasma jet since it could have only transient existence under normal conditions. Marynowski et al. note that two general avenues of approach are available:

The first "involves a controlled change in the path of the thermodynamic state (temperature and/or pressure) of the system, from plasma-jet to ambient conditions, so that the normal ambient equilibria are kinetically suppressed in favor of recombination reactions that lead to desirable metastable products. Techniques involving expansion of the reactants through a de Laval nozzle, quenching by contact with a cooled surface, or by injection of a cold inert medium, or combination of the above, fall into this avenue."

"The second avenue, instead of depending on preferential recombinations of plasma-jet species, involves interactions between these species and an independently introduced reactive medium. In this avenue are such techniques as spraying a reactive liquid (or solid) into the jet, dispersal of the jet gases through a reactive liquid, fluidization of a reactive solid with the jet gases, and transpiration cooling of an expansion nozzle with a reactive liquid. A special case... is the use of a quench liquid that is unreactive, but becomes reactive when it is partially pyrolyzed by contact with the jet gases."

Marynowski et al. emphasize the importance of quenching and note that this second step (after attainment of favorable equilibrium compositions) is far less developed. The highest practical quench rates have been attained by expansion of the hot gas through a de Laval nozzle. The actual quench rate required to maintain a desirable reaction composition, representing equilibrium at high temperature, depends on the kinetics of the various decomposition reactions. Since these high-temperature kinetics are generally not known, it is not possible to predict the approach to frozen equilibrium which would be obtained with any given quench rate.

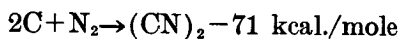
The third step in the process, when using a de Laval nozzle, is to couple the nozzle with some device for extracting the kinetic energy from the gas to prevent reheating. The ideal way is to use a turbine, thus providing means for converting part of the energy in the gas

stream back into electrical energy. Following the turbine, conventional liquid-spray techniques may bring the reaction mixture to temperatures appropriate for recovery of reaction products.

As *Industrial and Engineering Chemistry* (72) points out, practical applications for electric-arc-induced reactions go back to the turn of the century when Birkeland and Eyde developed an industrial process to synthesize nitric oxide from air using an electric arc. The process was used commercially in Norway, until superseded by the Haber-Fink process, which was more economical and produced nitric acid directly from ammonia by oxidation. Schonherr reported another nitrogen-fixation process in 1909. The high-voltage or Huls arc, a gas-stabilized arc with special geometric configuration, was developed for the fixation of atmospheric nitrogen. Baumann of Chemische Werke Huls reported the development of a process for synthesizing acetylene from saturated hydrocarbons using this high-voltage arc. Many of the reactions that have been studied since commercial arc-plasma generators became available have been concerned with the fixation of nitrogen, although reactions between carbon and hydrogen have also been studied.

SYNTHESIS OF CYANOGEN

Leutner (67) used the plasma jet to prepare cyanogen according to the endothermic reaction:



Carbon vaporized from an ordinary graphite cathode was reacted with a nitrogen jet, and with an argon jet into which nitrogen was fed. Both methods gave the same results—conversion of up to 15 per cent of the carbon input even with varying electrical characteristics and carbon-nitrogen ratios. The unconverted carbon was collected as a very fine soot.

One-fourth-inch-diameter graphite cathodes supported by a tight-fitting water-cooled copper holder were used. Since the consumption of the cathode was relatively rapid, a device was used to feed the cathode continuously toward the anode annulus so that the electrode distance was kept constant. Both ordinary and pyrolytic graphite were tried, but the latter proved to be practically nonconsumable because of high heat conduction. The anodes were copper, with ordinary thin graphite inserts. Gas-flow rates varied from 3 to 30 liters per minute; power input, from 5 to 14 kw.; and carbon consumption, from 0.25 to 2.25 gpm.

Yields of cyanogen did not improve with measures designed to give fast quenching—in fact, fast quenching had a reverse effect. This

was explained as due possibly to a too-short reaction time, or to a catalytic decomposition of cyanogen when contacting the copper of the cooling device. The reaction time in the plasma flame was calculated to be in the range of 5 to 50 milliseconds, depending on the gas-flow rate. Reaction temperature, although not measured, was known to be in excess of 4,000° C., since all carbon was vaporized.

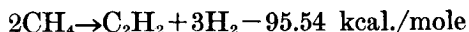
In addition to cyanogen and soot, some paracyanogen could be detected qualitatively in the reaction products.

It was ascertained that the economy of the process depends almost solely on the power consumption. With electric energy at 6 mills per kw.-hr., the electric-power cost per pound of cyanogen produced in the experimental apparatus was \$1.40. Inasmuch as cyanogen is a relatively expensive chemical, and power costs depend on the site, the results of this experiment indicate possible industrial interest.

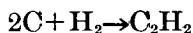
Stokes and Knipe (70), in a paper published in 1960, mention the use of fluidized carbon powder as a source of carbon in the plasma synthesis of cyanogen. In the experiment described, carbon powder fluidized in nitrogen was injected into the plasma by means of a feed ring. At the plasma temperature, the carbon was vaporized, and a cold finger was used to quench the gases. Unreacted carbon condensed in the reaction chamber, and the cyanogen formed was condensed in external freeze-out traps with dry ice. The reported conversion, based on carbon, was 2 percent.

ACETYLENE PRODUCTION

Several approaches have been taken to the production of acetylene by plasma reactions. The reactions involved are:



and direct synthesis from the elements:



Leutner and Stokes (80) tried three different methods: feeding carbon into a hydrogen-plasma jet; using a methane-plasma jet; and feeding methane into the flame of an argon-plasma jet. The jet, in each case, consisted of a 1/8-in. diameter, 2 percent thoriated-tungsten cathode and a water-cooled copper anode.

In the production of acetylene by feeding carbon into a hydrogen jet, a 1:3 mixture of hydrogen and argon was used. The carbon source was a 1/8-in. thick graphite insert in the anode, which sublimed and reacted with hydrogen. A bright, stable plasma jet resulted from a gas flow of 6 to 10 liters per minute with the 1:3 ratio. Because of the loss of graphite, the jet became unstable after 2 to 5 minutes. The jet was quenched in a water-cooled copper chamber

and the gases were passed through four dry-ice traps, connected in series. The remaining gases were collected in a gas holder.

Reaction products consisted of large quantities of hydrogen, argon, and acetylene, and some methane. No other hydrocarbons were found. Sixty to eighty percent of the consumed graphite was collected in the chamber as fine soot.

The second method of producing acetylene by using a methane-plasma jet was unsuccessful. In this attempt methane-argon mixtures of proportions from 1:4 to 1:30 were tried.

Production of acetylene by feeding methane into the flame of an argon-plasma jet also was tried. In this experiment a water-cooled feeding annulus was added to the anode by which the methane was introduced at an angle of 90° to the argon jet. Almost all the methane was converted to acetylene and hydrogen in this experiment. There was little formation of soot. Less than 10 percent of the original methane remained unreacted.

Typical percentage yields, based on carbon input (via CH_4), obtained in this experiment were:

Percent:	Compound
80.1	C_2H_2
5.7	Soot
7.1	CO_2
7.1	CH_4

The freezeout trap system was used. An average temperature of $12,000^\circ \text{K.}$ was obtained in the argon-plasma jet.

It is interesting to note that this plasma-jet experiment gave an 80 percent yield as compared with the 12 to 14 percent yield normally obtained from the high-current arc process for acetylene production. The yields are even higher when compared with the presently used pyrolytic process. In the final report under contract Nonr 3085 (02) covering the production of acetylene and hydrogen cyanide, Grosse et al. (68) discuss the use of a radio-frequency plasma jet as a potential commercial technique. The reaction chosen was the formation of acetylene from methane as previously shown.

Certain modifications of the reaction chamber were necessary to overcome direct electrical discharges to the carbon particles deposited through decomposition of the methane. These modifications made a pure methane plasma impossible and consequently the combination of helium and methane was chosen.

In the trial runs, the plasma jet was started in the helium atmosphere and methane was introduced at a maximum input of 168 cc./min. Helium flow varied from 0.1 to 1.5 liters per minute. The yield exceeded 28 percent conversion based on the carbon input. However,

in comparison to the investigations using the dc jet previously mentioned, the production yield was lower.

According to the Thermal Dynamics Corporation (81), several experiments have proved the feasibility of producing acetylene from kerosene, using a plasma torch. Preliminary runs gave yields as high as 18 percent acetylene in the gas produced by this decomposition. Yields as high as 25 percent are believed to be possible with improved equipment. Present commercial cracking processes yield from 4 to 9 percent. Details of the experiments are not given.

Damon and White (79) have selected the manufacture of acetylene as one of the applications for plasma processing of potential interest to the petroleum industry. Methane is one of the gases proposed for cracking. They introduce the concept of the plasma as a reactor "pre-heater" or "superheater" to supply a portion of the energy rather than all of the energy in a suggested procedure which is described in some detail.

Baddour and Iwasyk (75), in their studies of the reactions of elemental carbon and hydrogen at temperatures above $2,800^{\circ}\text{K}$., used three schemes for achieving high temperatures, one of which was a plasma-jet reactor. The plasma jet used failed to provide sufficient carbon at temperatures in excess of $2,800^{\circ}\text{K}$., and a high-intensity arc reactor proved to be superior for studying the reactions. The arc reactor gave up to 23.8 percent by volume.

Anderson and Case (74) used the methane-decomposition reaction to gather experimental information for comparison with predictions based on available thermodynamic and kinetic data. The experimental equipment consisted of a hydrogen-plasma torch, a reaction chamber, and a water-quench chamber. An arc was struck between a tungsten electrode and a water-cooled, copper, annular anode. Hydrogen flowed around the cathode and through the anode, where it was heated to temperatures between $5,400^{\circ}$ and $18,000^{\circ}\text{Rankine}$. The hot hydrogen stream entered the reaction chamber, where it was mixed with a methane feed. The gas mixture leaving the reaction chamber was water-quenched and its components analyzed.

They predicted the optimum cracking conditions for methane, taking the formation of diacetylene and ethylene into account, would be an acetylene yield of 30 percent, an acetylene concentration in the product gas of 16 percent, and an energy requirement of 340,000 Btu/lb.-mole of acetylene, respectively—indicating an excellent agreement with the values calculated from the theoretical analysis.

A report by the National Academy of Sciences (82) states that the Linde Company has investigated the production of acetylene, using the plasma jet and natural gas. The plasma-jet process is said to provide

more efficient transfer of energy to the feed stream than does the open-arc process used in Germany. Mention is made of the possibility of producing impure acetylene merely by submerging a plasma jet in kerosene.

SYNTHESIS OF HYDROGEN CYANIDE

Several reactions for the synthesis of hydrogen cyanide have been studied. Grosse, Leutner, and Stokes (68) describe experiments in which the compound was prepared (1) from the elements; (2) from carbon and ammonia; (3) from methane and nitrogen; (4) from ammonia and methane; and (5) from ammonia and carbon monoxide.

Synthesis directly from the elements proceeds according to the reaction:



A possible way to bring about this reaction would be to feed a suspension of pulverized carbon in hydrogen into a nitrogen-plasma flame and fast-quench the exit gases. However, to simplify equipment, a consumable, ordinary-graphite cathode was used as the carbon source. The cathode was moved continuously toward the anode to compensate for vaporization and to maintain uniform electrical characteristics.

Over 50 percent of the carbon input was converted into HCN. Acetylene was formed as a byproduct in 13- to 14-percent yields. Other hydrocarbons, in yields less than 20 percent were formed, and the balance of the carbon was collected as finely divided soot in the cooling chamber.

The authors considered the low-vaporization rate of the graphite cathode a limiting factor, which suggests that another method of introducing carbon would be desirable in any proposed commercial process. There was evidence to suggest that higher HCN yields might be possible with less-pronounced quenching.

The reaction using carbon and ammonia as starting materials was essentially the same, since ammonia decomposes quantitatively into nitrogen and hydrogen while passing through the plasma flame. The only difference in the process was that ammonia was fed into the plasma jet instead of hydrogen, and the vaporization rate of the carbon cathode was forced. HCN formation up to 39 percent, based on carbon input, was obtained, with the byproduct acetylene running from about 7 to 18 percent. Slower quenching gave the best yields.

In the experiments using methane and nitrogen as starting materials, the expectation was that CH_4 would decompose into the carbon and hydrogen needed for the reaction. Both graphite and nonconsumable 2-percent thoriated-tungsten electrodes were used. Into a pure

nitrogen-plasma flame, methane was added through a gas-feeding ring.

Yields of HCN from 21.1 to 45.7 percent resulted when graphite cathodes were used, with acetylene yields ranging from approximately 39 to 46 percent, all based on total-carbon input. With tungsten cathodes, HCN yields were 19.5 to 23.2 percent, with acetylene yields from 32 to 62 percent. (When a pyrolytic-graphite cathode was used, a carbon-nitrogen proportion of 1:7.7, 91.3 percent of the total-carbon input was converted into HCN and C_2H_2 .) The experiments were regarded as important from the standpoint of the nitrogen fixation achieved. In some cases, more than 20 percent of the nitrogen input was converted into HCN.

The experiments with ammonia and methane as reactive agents were undertaken in order to switch from consumable to nonconsumable cathodes. Methane serves as a carbon and hydrogen source, while ammonia is a nitrogen source. Conversion to HCN and acetylene, based on carbon input, ranged from 60 to 75 percent using either argon or nitrogen as plasma gases. HCN formation was favored when nitrogen was used in excess. With argon as the plasma gas, the formation of C_2H_2 had preference, with the preference depending on the quenching rate. This is explained by the fact that acetylene is the more endothermic compound. Thus, faster quenching rates favor the formation of acetylene.

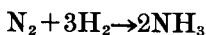
Grosse (68) and his associates also investigated the use of the radio frequency unit for the preparation of hydrogen cyanide. Using the device previously mentioned for the production of acetylene, the researchers started with helium and slowly changed to nitrogen. Methane was introduced to begin the reaction and products were collected and analyzed. While the use of a radio-frequency plasma jet is feasible, the results on a comparative basis still favor the dc plasma unit originally used by the authors.

The electrical power required to produce one gram mole of HCN was determined to be 2.4 times higher than that required in the dc unit.

FIXATION OF NITROGEN

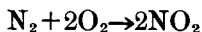
The fixation of nitrogen has, of course, always been one of the major applications for arc-induced reactions. As noted earlier, experiments on the production of hydrogen cyanide from methane and nitrogen, using nitrogen as the plasma gas, led to significant fixation of the nitrogen in the form of HCN.

Grosse, Leutner, and Stokes (68) report an attempt to synthesize ammonia by feeding hydrogen into the flame of a nitrogen plasma, according to the reaction:



The reaction, however, is exothermic, and no NH_3 could be detected in the collected reaction products. Small amounts of hydrazine (N_2H_4)—which has a negative heat of formation—were formed.

The reaction :



is endothermic, as are the reactions leading to other nitrogen oxides. Thus, oxidation would appear to be a feasible method of nitrogen fixation via plasma techniques.

Stokes and Knipe (70) reported the preparation of nitrogen dioxide by injecting oxygen into a nitrogen plasma through a feed ring. A cold finger was used to quench the gases, and the nitrogen dioxide formed was collected in traps and cooled with dry ice. There was evidence also of the presence of NO , which was expected because of the excess of nitrogen in the reaction chamber. The average conversion to oxides, based on oxygen, was only about 2 percent.

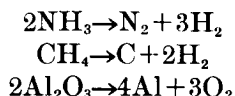
Grosse, Leutner, and Stokes mention attempts to fix nitrogen via oxidation, using modified equipment. Oxygen was fed into the nitrogen-plasma jet in stoichiometric ratio. However, only 2.03 percent of the total nitrogen input was converted to NO . This is a poor rate of fixation as compared with conversion into HCN .

Another approach to nitrogen fixation is formation of a metal nitride. Stokes and Knipe succeeded in preparing nitrides of titanium and magnesium. The nitrides were produced by fluidizing the metal powders in nitrogen and feeding into a nitrogen-plasma jet. Average nitrogen flow was 2.5 liters per minute. A total power supply of 9.5 to 10.5 kw. was supplied to the plasma. Titanium feed rate was 1.72 grams per minute. A lustrous, golden, crystalline compound was obtained. The average yield was 30 percent using a cold finger for quenching. Magnesium nitride was prepared by fluidizing the powdered metal and injecting into the plasma. Nitrogen flow was 2.5 liters per minute, and power to the plasma was 12 to 15 kw. The yield averaged 40 percent, and the resulting nitride was a dull yellow color. Magnesium nitride decomposes rapidly in the presence of water, yielding ammonia.

DECOMPOSITION REACTIONS

As noted earlier, the plasma jet offers possibilities for carrying out two types of reactions: decomposition and synthesis. Introduction

of a compound into a plasma flame should result in the dissociation into elements or less-energetic compounds, thus:



Conceivably, the method may have application to the reduction of oxides.

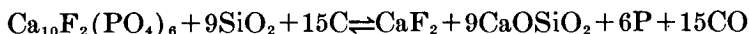
Grosse, Leutner, and Stokes (68) also describe investigations on the reduction of alumina. It was believed that Al_2O_3 would decompose into its elements upon passing through a plasma flame, and that with fast quenching recombination might be prevented.

Several experiments were made with an argon-plasma jet. Finely ground Al_2O_3 was fed as a suspension in either hydrogen or methane into the plasma flame. Residence time of the particles in the flame was calculated to be in the range of 5 to 20 milliseconds. The solid products formed, after fast quenching with a water-cooled funnel, proved definitely to contain aluminum metal upon analysis, although conversion was low.

Damon and White (77) have proposed a plasma-jet reduction process for the production of elemental phosphorus from phosphate rock and have described both the thermodynamic and economic considerations leading to the conclusion of feasibility.

According to them, elemental phosphorus of sufficient purity for food-grade and related products must now be produced in the electric furnace for reasons of economics. When phosphorus is shipped in the elemental state prior to conversion to phosphoric acid, the freight savings are analogous to those achieved by shipping elemental sulfur to the plant location where sulfuric acid is required. Thus, electric-furnace phosphoric acid via phosphorus is competitive with wet phosphoric acid in fertilizers under certain circumstances.

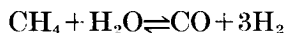
Present thermal-reduction processes are based on the reduction of phosphate rock with coke and a siliceous flux, according to the reaction:



A blast-furnace process and an electric-furnace process for the reduction have been developed and put into operation. A plasma-jet process would appear feasible.

The phosphate rock used would consist mainly of fluorapatite, $\text{CaF}_2\text{Ca}_3(\text{PO}_4)_2$. The bonding of CaF_2 to tricalcium phosphate would be easily broken under the proposed operating conditions for the process. Hence, the main reactions would involve CaF_2 and $\text{Ca}_3(\text{PO}_4)_2$.

Reformed natural gas obtained by the plasma-jet reaction of methane with steam would be used as the reducing agent:



The mixture of CO and H₂ produced by the plasma jet and kept at a high enthalpy level would receive a feed stream of extremely fine phosphate rock particles in a thick slurry with a liquid hydrocarbon.

The primary reactions would be:

- (a) $\text{Ca}_3(\text{PO}_4)_2 + 5\text{H}_2 \rightleftharpoons 3\text{CaO} + 5\text{H}_2\text{O} + 2\text{P}$
- (b) $\text{Ca}_3(\text{PO}_4)_2 + 5\text{CO} \rightleftharpoons 3\text{CaO} + 5\text{CO}_2 + 2\text{P}$
- (c) $\text{CaF}_2 + \text{H}_2 \rightleftharpoons \text{Ca} + 2\text{HF}$
- (d) $\text{CaF}_2 + \text{H}_2\text{O} \rightleftharpoons \text{CaO} + 2\text{HF}$

Thermodynamic studies indicate that the reduction reactions should be feasible above 2,100° K., and that deleterious side reactions could be avoided by keeping reaction temperatures in the range from 2,100° to 3,400° K. It is believed that reaction rates should be fast enough to present no design difficulties. Detailed process-design studies would be needed to verify certain points.

According to the projected plan, the phosphorous produced would not need to be quenched quickly, as long as it was kept in a reducing atmosphere. Such an atmosphere would exist. The quenched phosphorus would be shipped under a water blanket in molten slate, as currently practiced. However, where phosphoric acid is desired at the site, consideration might be given to burning the phosphorus to the pentoxide prior to power recovery from the gas stream.

This proposed process illustrates the ingenuity that can be exercised to design around the plasma phenomenon. At the time of this writing it could be established that several companies and research organizations were studying plasma-jet reactions and equipment with commercial and patent objectives in mind. All of the known work, however, is regarded as proprietary for obvious reasons.

PLASMA-JET REDUCER GAS

The process proposed by Damon and White (77) for the production of phosphorus is dependent upon the production of a reducer gas by the reaction:



This is an endothermic reaction that could be basic to many reducing processes utilizing plasma-jet principles.

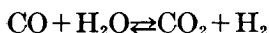
Damon and White (79) selected this reaction and related reactions leading to the production of reducer gas for special study. They

visualize "plasma-jet packaged units" as being developed for utilization in many processes requiring a reducing gas. The economics would depend largely on supplying a desirable gas mixture at a higher temperature level than is possible by conventional reformer-gas operations. It is believed that metallurgical and many other high-temperature reduction processes could be developed around the reaction.

It is pointed out that there are essentially three satisfactory means of obtaining large quantities of hydrogen from hydrocarbons; namely, steam reforming, partial oxidation, and as a byproduct from catalytic reforming at petroleum refineries.

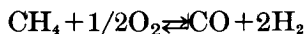
Most nonrefinery processes using hydrogen in large quantities now get it from either partial oxidation or steam reforming. These processes make hydrogen available from methane, other light hydrocarbons, or fuel oils at nonrefinery sites. Refineries having hydrogen demands above and beyond their production of off-gas hydrogen could also make use of these processes.

Steam reforming, the most widely used method of producing hydrogen, frequently encompasses two reactions, thus:



The first is carried out catalytically with aluminum oxide. The second, the water-gas shift reaction, increases the amount of hydrogen formed. It is catalyzed with an iron-base catalyst. Carbon dioxide and excess steam are stripped from the gas to give a relatively pure hydrogen. The water-gas shift reaction can be eliminated if a reducer gas consisting of CO and H₂ is desired.

The partial-oxidation process may be represented thus:



It is carried out noncatalytically at appropriate pressure and temperature and is becoming economically competitive with steam reforming, largely as a consequence of the development of compact plans for the production of low-cost oxygen.

The plasma jet, according to Damon and White, could serve as an ideal reactor for the production of hydrogen from hydrocarbons by steam reforming, partial oxidation, or a combination of both. To illustrate the use of the plasma jet, the thermodynamics of the steam reforming of methane were considered in detail and pronounced feasible.

The proposed process for steam-methane reforming by the plasma jet would operate at a temperature of 3,000° to 6,000° F., which is

considerably higher than the normal 2,200°-F.-catalytic process. Thus, it would provide a high-temperature-reducing gas for metals and other high-temperature processes. It is visualized that the plasma arc would operate on hydrogen, which would enrich the reducing gas. If carbon deposition should prove to be a problem, the main reaction could be held near 3,000° to 4,000° F., and a supplemental plasma-jet superheater could be used immediately downstream to achieve the desired reducing-gas temperature.

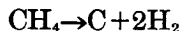
At these high temperatures, essentially complete conversion of methane to CO and H₂ at steam to methane ratios as low as 1:2 is an expectancy. The steam could be injected into the plasma arc with the hydrogen or into the reaction chamber in or immediately downstream from the flame.

The proposed process would need to be integrated with a subsequent process that utilized the reducing gases in order to take advantage of the high temperature of these gases. Thus, finely divided ores or other materials would be fed downstream to carry out high-temperature reductions. Desirably, the residual energy in the tail gas would be recovered with turbines or other equipment. The water-gas shift reaction could be linked to the process for manufacture of hydrogen, which could be used in part as the hydrogen for the plasma.

Damon and White suggest the development of small packaged hydrogen plants, based on plasma-jet steam reforming, for use where the need for small quantities of hydrogen exist (such as in the industrial hydrogenation of vegetable oils) at some distance from large-quantity sources of supply. These packaged units could use natural gas or propane as the hydrocarbon source.

PYROGRAPHITE FORMATION

The decomposition reaction:



has practical value in the formation of pyrographite. Pyrographite is of interest because of its superior high-temperature properties. It has greater oxidation resistance and greater flexural strength than ordinary graphite, and above 3,000° F. its strength-to-weight ratio is the highest among the materials considered for high-temperature applications. Above 5,000° F. its strength is 40 times that of tungsten. Pyrographite has a homogeneous, columnar structure of closely packed graphite crystals, with strong bonds along the flat planes, but weak bonds between layers. This provides good heat conduction along planes of crystal orientation, but poor conduction in perpendicular planes. This property makes pyrographite useful as a liner for

rocket nozzles and as a heat-shield material for missile nose cones. It also has uses, or potential uses, in industry as a material for crucibles and hot-pressing dies and in nuclear applications.

One fabrication method involves passing heated methane or propane over a hot mandrel of the desired shape. As the gas is broken down, the carbon is deposited on the mandrel while the hydrogen passes off. Under controlled conditions, a pyrographite part with proper crystal orientation is formed.

According to the Thermal Dynamics Corporation (83), pyrographite has been formed with the plasma torch. The flame is made to impinge upon the revolving mandrel through a slot in an insulated heat shield. Methane is blown onto the white hot ring on the mandrel and decomposed into carbon and hydrogen. The evolving hydrogen forms an atmosphere that protects the growing deposit. The company believes that the technique holds promise for improved economics and speed over present production methods.

PETROCHEMICAL PRODUCTION¹⁰

The ability to effect decomposition and synthesis reactions with the plasma jet has suggested its application to petroleum refining and petrochemical manufacturing processes. The petroleum industry as a whole is responsible for nearly 50 percent of the chemical production in the United States through its raw materials and petrochemical processing plants, and, if plasma techniques should prove useful in refining, reformation, and synthesis processes, this might well be an area for extensive utilization.

Informal discussion with management and research personnel within the petroleum industry has led to the conclusion that the industry has a definite interest in the subject and in sponsoring proprietary research in plasma-jet processing. The literature, however, is extremely sparse—which may arise from the fact that all industrial research programs in progress are in early exploratory stages and also from the fact that companies would tend to withhold publication until patent positions and other proprietary values had been established. One publication, arising from research at the Standard Oil Company of Ohio and stated to be a part of a 4-year program, deals not with petroleum cracking or the synthesis of chemical products, but with the properties of nickel fume generated in a plasma jet. The intent of this research was to investigate a potential means for producing ultrafine nickel-oxide powder.

¹⁰ This section is from "Potential Applications for Plasma-Jet Processing in the Petrochemical Industry," an unpublished specialized study done previously for NASA by Clyde Williams and Company.

The National Academy of Sciences-National Research Council report "Development and Possible Applications of Plasma and Related High-Temperature Generating Devices" (82) briefly summarizes work known to have been done with the plasma in the chemical field up to 1960. It mentions the pyrolysis of hydrocarbons to produce carbon black and some interest in the possibility of reacting hot hydrogen with relatively cool hydrocarbons to accomplish cracking without carbon production. It also confirms that "an unknown amount of research in high-temperature chemistry is being carried on in laboratories of certain large companies for which no information is presently available."

The same report, in a chapter on the chemistry of plasma flames, suggests that research in the plasma regime above $5,000^{\circ}\text{K}$. should mainly be concerned with problems that can be solved only via the extremely high temperatures attained. A gross need is stated to exist for original ideas and unique applications of plasma generators to chemical systems. Referring specifically to the petrochemical field, the report notes that "high-temperature research in the wide area of chemical synthesis is aimed at the production of new materials and the development of better processes for known materials. Thermal cracking and similar processes for the reformation of hydrocarbon compounds are the means of manufacturing a large group of so-called synthetic chemicals, as well as of commercial liquid and gaseous fuels. Various processes for cracking petroleum with or without catalysts have been in successful operation for many years, and the manufacture of petrochemicals has become a large industry. . . . Only a small fraction of the total present activity actually calls for temperatures above $2,000^{\circ}\text{C}$."

While this statement defines the temperature region where the plasma generator might be most useful in petrochemical work and tends to suggest caution as to practical applicability in competition with existing successful processes, it does not preclude petrochemical application or ideas, such as those advanced by Damon and White, for use of the plasma jet as a supplemental superheater in connection with conventional processes.

As a reaction activator, the plasma-derived VSRS has various interesting possibilities. One is at the other extreme of the temperature scale—namely, in low-temperature processes, where it may be desirable to impart energy to specific molecules without raising the temperature, thereby avoiding unwanted side effects. Another is the activation of reactions by applying radiation over narrow energy bands to produce selectively certain desired isomers. In other instances, VSRS holds the possibility of replacing catalysts that are

used in petrochemical processes. Radiation activation would eliminate problems of catalyst poisoning.

Many of the studies conducted to date on chemical processing with the plasma jet (and described in a previous section on "The Plasma Jet in Chemical Processing") relate to raw materials, such as methane and hydrogen, produced and used in quantities by the petroleum industry, or to reaction products, such as acetylene, that are important intermediates in petrochemical operations. Thus, much of plasma-jet processing research has application to the whole of the petroleum industry.

Production of acetylene by the introduction of hydrocarbon liquids or gases into a hydrogen plasma, followed by a water quench has been suggested. As noted by Phillips and Ferguson (84), a new process for producing acetylene at substantially lower cost could have significant effect on the U.S. chemical industry. Presently, domestic production is divided between processes based on the partial combustion of hydrocarbons and the calcium-carbide process, which is more economical where there is low-cost power.

Damon and White (79), in their study, listed the various process currently used in petroleum refining. They concluded that it is doubtful that the plasma jet will find application in these processes. The reason is the highly developed and economical nature of refining processes. However, they suggest that the plasma jet might at least be considered for use in connection with several processes. It might be possible, for example, to crack high-molecular-weight oils in the presence of hydrogen at much higher temperatures and much shorter residence times than presently are produced. An advantage would be lower capital investment in the plant.

Three refinery processes, in particular, are singled out for at least consideration of plasma application: the delayed coking, catalytic hydrocracking, and platforming processes. In the first, the objective would be higher yields of valuable liquid products through more precise cracking conditions in the presence of hydrogen with heavy petroleum residuum. In catalytic hydrocracking, the objective would be higher yields at higher production rates and, as a result, lower capital investment. Platforming is a very successful process for making higher octane gasolines by the synthesis of aromatics, using a platinum-containing catalyst. It normally entails the use of three reactors in series with preheaters before each reactor. A plasma preheater might be used to eject the proper amount of heat into the system at any desired point and thereby produce improved yields of desired aromatics.

Damon and White note that there are only three basic steps in making petrochemicals from crude oil; namely, cracking, synthesis, and

polymerization. The plasma reactor—and especially the plasma heater—might be applied to certain specific reactions.

In connection with the manufacture of acrylonitrile—the basis for acrylic fibers—they suggest the possibility of using the plasma reactor in the process whereby acrylonitrile is produced by the direct catalytic air oxidation of propylene and ammonia. This is a single-step process developed and used by the Sohio Chemical Company for production of this important petrochemical.

It might be noted that other processes for making acrylonitrile are based on raw materials that could be produced by the plasma-jet reactor, using, in some cases, methane, a petroleum-field hydrocarbon, as a feed. For instance, acrylonitrile can be made in a one-step process directly from acetylene and hydrogen cyanide. And acetylene and hydrogen cyanide have been made in the laboratory simultaneously in very high yields from methane and nitrogen via the plasma reactor. The American Cyanamid Company's process of making acrylonitrile from cyanohydrin also uses hydrogen cyanide as a reactant—a nitrogen-containing compound that can be easily produced in good yields, at least in laboratory equipment, by plasma-jet processes.

Acrolein is a commercially valuable intermediate used in the synthesis of glycerin. Several processes for its manufacture are based on the oxidation of propylene. Damon and White suggest that the plasma reactor should be checked as a preheater and source of inerts to displace the steam now used in the Standard of Ohio process.

Phthalic anhydride is an intermediate used in the manufacture of plastics. Historically, it has been produced from coal-tar naphthalene, but it can also be made from ortho-xylene. The demand for phthalic anhydride has increased to such an extent that coal-tar naphthalene is being supplemented by petroleum naphthalene and o-xylene as raw materials. The plasma reactor could have application for the vapor phase catalytic oxidation of both naphthalene and o-xylene to phthalic anhydride. Reaction rates are fast, being about 0.3 to 1.0 second at temperatures of 600° to 800° F. The role of the plasma would be as a preheater to give instant heat to the feedstock. An objective for such application would be to improve yield efficiency.

The use of the plasma reactor as a preheater might also give improved yields in production of maleic anhydride. It is produced mainly from benzene by air oxidation in the vapor phase, using a catalyst. Maleic anhydride is an important intermediate basic to the production of polyester resins, alkyd coatings, agricultural chemicals, paper sizes, plasticizers, and drying oils.

Most of the adipic acid required for manufacturing nylon is made by oxidizing cyclohexane to cyclohexanol-cyclohexanone and, subsequently, to adipic acid. Damon and White believe there would be

merit in the conduct of a research investigation aimed at the use of the plasma as a preheater to devise a radically new process for oxidizing cyclohexane to adipic acid in one step. Presumably, precise control of temperature and short residence time give logic to the possibility of eliminating one of the oxidation steps.

Short residence time at reaction temperature is also a factor in the suggestion that the plasma reactor might be used to oxidize benzene by air directly to phenol. A process developed by the Scientific Design Company, Inc., which is based on the direct oxidation of benzene to phenol, is regarded as the most likely one for plasma application. Short residence time, followed by quick quench to stop the oxidation of phenol into such products as benzoic acid and biphenyl, might give increased yield of phenol.

OTHER SUGGESTED REACTIONS

As previously noted, there is much evidence of proprietary research in progress in large industrial companies and research institutions. Mentions of various investigations are made in the literature without detail or elaboration. These cursory references suggest the direction of thinking regarding the application of plasma-jet reactors.

Damon and White (79) have indicated that various undescribed reactions have been studied theoretically. Such include the synthesis of urea from carbon dioxide and ammonia; the production of olefins of four carbons or more by cracking and thermal dehydrogenation; and the production of silicon chloride from silica and hydrogen chloride, or from silica, carbon monoxide and/or hydrogen and chlorine.

Thermodynamic considerations seem to rule out the feasibility of synthesizing urea, except at lower temperatures, at which the reaction rate would be too slow. The production of olefins, however, appears to be thermodynamically, and possibly economically, feasible. Control of the reaction system to give specific products probably would be difficult. It is believed that this type of reaction could be successful if it were used in conjunction with the proper catalysts placed downstream from the tail flame of the plasma jet.

Silicon tetrachloride is important as an intermediate in the production of semiconductor material and is also used in the manufacture of silicones. Plasma-jet production, from silicon dioxide and hydrogen chloride, according to Damon and White, is not thermodynamically feasible, but production from carbon monoxide and/or hydrogen and chlorine with SiO_2 should be.

Phillips and Ferguson (84) reported that Stanford Research Institute has performed work on synthesizing high-melting compounds. When hafnium carbide and hafnium boride were injected concurrently into a plasma stream impinging upon a water-cooled turntable, ternary

compounds were deposited. Stanford has also tried direct synthesis of organic-metallics by contact between an organic liquid or vapor stream and a metal activated, perhaps ionized, in a plasma jet. An arc process for production of alkyl and aryl silanes from elemental silicon and hydrocarbon gas is based on this principle.

In the Stanford experiments the metal powder is injected with a stream of inert gas into the plasma. This contacts the recycling liquid-organic reactant and vaporizes a portion of it. Vapor flows with the inert gas through the absorber, where condensation occurs upon contact with the stream of recycled organic reactant. The portion of the organic-feed stream which passes to the bottom of the reactor as a liquid is distilled to separate the less-volatile products of interest from the unreacted material which is recycled.

Alternative arrangements are possible for producing these organic-metallic reactions, according to Phillips and Ferguson. The metal could be fed to the plasma as a liquid or as a vapor generated by an auxiliary arc, or metal reactants could be replaced with volatile compounds of metals, such as iron and nickel carbonyl. Indirect condensers or adsorbers for cooling the effluent gas stream and collecting volatile products might be used. And to prevent the destructive action of electrons on the organic reactant, magnetic or electrostatic fields might be applied to the plasma to separate metallic ions from electrons.

The research, as reported, was directed specifically toward the preparation of new, thermally stable species, but could have possible application for the production of such compounds as tetraethyl lead, dimethyl zinc, dibutyl tin, and organosilanes.

Synthesis of fluorocarbons by the Minnesota Mining and Manufacturing Company was reported at a conference on plasma phenomena, held in Washington in April 1959 (84), under the auspices of the Materials Advisory Board, National Academy of Sciences, and National Research Council. No details were given.

A gas-phase reaction that occurs in an electric arc well above 3,000° K. has been reported by Tennessee Valley Authority investigators. They produced phosphonitrilic compounds, PN and analogs, by passing a stream of nitrogen containing phosphorus vapor through an arc. These compounds are too resistant to hydrolysis to be suitable for fertilizer materials, but the research suggested the synthesis of ternary compounds by gas-phase reactions in the electric arc, and investigators at Stanford Research Institute (85) succeeded in producing thermally stable compounds of phosphorus, nitrogen, and sulfur. Presumably, the plasma jet could be readily adapted for such syntheses.

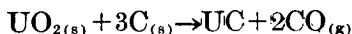
Vapor-phase halogenation reactions with high-intensity electric arcs have been suggested by Sheer et al., of the Vitro Corporation (82) as

one of several methods applicable to extractive metallurgy. When ore-bearing electrodes are vaporized in a chlorine atmosphere, and especially when chlorine gas is injected directly into the plasma flame, the metal oxides can be converted quantitatively to chlorides in the vapor state. The effluent gas stream consists essentially of a mixture of metallic chlorides and carbon monoxide. Since the boiling points of many of these chlorides are widely separated, halogenation facilitates separation of the metallic constituents. The chlorides of Be, Fe, Al, Cb, and Si may be caught in suitably designed condensers below 500° C. The technical feasibility of such separations has been demonstrated with such ores as beryl, kaolin, and borax. Presumably, in a commercial plasma halogenation, nonconsumable electrodes would be used, and the ore would be introduced as a suspension.

Fixed-bed chlorinations have been used industrially for many years. The temperature of the plasma, although not essential for the reactions, accelerates reaction rates. Fast reaction rates should enable high-speed flow processes capable of heating relatively large hourly tonnages, even though the quantity of material in the reaction zone is always small.

The possibility of using plasma-jet halogenation processes when the halide itself is a final product, rather than an intermediate, would seem worthy of consideration by chemical-product producers.

The preparation of metal carbides by the high-intensity arc has been studied: Gibson and Weidman (69), of Vitro Laboratories, in a manuscript prepared for presentation before a symposium of the American Institute of Chemical Engineers, describe the preparation of uranium carbide from reactor grade UO_2 or U_3O_8 and reactor-grade carbon or graphite. The solid reactants are homogeneously dispersed in a consumable anode, which is arced in a vacuum-arc chamber to produce uranium carbide and carbon monoxide. The gas is exhausted by conventional pumping equipment. Electrons emitted from the cathode bombard the anode resulting in an anode temperature of 4,000° to 5,000° K. to bring about the reaction:



The uranium carbide formed is near its boiling point of approximately 5,000° K. It drips to the bottom of the chamber, forming spheres as it solidifies. A plasma flame is produced by the evolving CO, but the process is probably more correctly called an arc process, since the reduction reaction occurs in the film of molten metal covering the face of the anode.

An advantage of the process is that it produces high-purity uranium carbide, of interest as a nuclear fuel. According to the authors, the concept of introducing solid chemical reactants into a reaction zone at

temperatures of 2,000° to 7,000° K. by means of the consumable homogeneous electrode provides several interesting advantages from a chemical engineering standpoint. These include the continuous and controlled manner in which reactants are fed and in which products and byproducts are removed and the fast reaction rates achieved. Disadvantages are that the process is generally restricted to refractory solids and endothermic reactions. Also, the reaction of very large quantities of reactants in short periods of time is not feasible.

FUTURE DEVELOPMENT

Chemical processing by the plasma jet is in such an embryonic stage of development that no one can be certain what the future portends. So many variations in introducing reactants, in temperatures, in methods of quenching, in integrating process with process, in isolation of products and byproducts, in recycling, and in use of residual heat are possible that the potential for continued development is great indeed.

Conceivably, multiple units could be used to generate active species for subsequent reactions at lower temperatures, including those of the exothermic type. The generation of free radicals, their isolation, and handling to produce desirable stable product is challenging.

Illustrative of the unusual applications is the use of a modified plasma jet to provide a high-intensity radiation source for the activation of photochemical processes. Called a "vortex-stabilized radiation source," this device developed by the Plasmatyne Corporation appears practical to activate low-temperature processes such as polymerization reactions. Radiation, rather than heat, is the energizing tool, but the radiation is produced by the plasma phenomenon. A different plasma light source requiring no gas flow and capable of operating on reactive as well as inert gases has recently been marketed by TAFA.

As previously noted, the cost of electrical power is an overriding economic factor, and price trends here are more favorable to proposed plasma processes than to chemical processes based on other energy sources. The areas for first commercial exploitation—if such does occur—should be those supplied with cheap hydroelectric power.

GLASS INDUSTRY

GENERAL

Several potential applications of the plasma jet in the glass industry have been installed in laboratories. There is good reason to believe that production applications will evolve. Specifically, cutting, glazing, spraying, and even repairing are some of the potential uses under investigation. Figure 2.25 illustrates uses for plasma flame in the glass industry.

FLAME POLISHING

The extremely high heat content and high heat-transfer rate of plasma flame make it useful in finishing the edges of manufactured glass pieces with a fine polish (brought on by surface melting).

PIERCING

Holes varying in size may be pierced in glass with plasma flame.

SPRAYED COATINGS ON GLASS

Plasma spraying is a process in which fine metal or ceramic powders are fed into an extremely hot plasma stream. The molted particles, traveling at high velocity, are impinged on the glass to form a tightly bonded coating. Almost any metal from silver to tungsten can be thus bonded to a glass surface. Various ceramics can also be sprayed on glass. The temperature of the glass may not have to exceed 300° F.

SOLDERING METAL TO GLASS

In applications where metal-to-glass joints are desired, glass parts, sprayed with a thin coating of copper, can be readily soldered to a metal part, using ordinary solder.

GLASS SPRAYED ONTO METAL

If handled carefully (because of softening range), glasses can be sprayed by a plasma process onto nearly any metallic or ceramic part. If the devitrification range and operating temperature coincide for a long enough period of time, however, the product will be crystalline rather than amorphous.

CRUCIBLE AND FURNACE MELTING

The plasma jet, with its soft, low-velocity flame and its high temperature and high heat-transfer rate, can be employed in crucible or furnace melting of glass. Controlled atmospheres can be readily maintained.

PROPULSION

While the only present use of the arc plasma jet thruster is in attitude and position control of spacecraft, results of work in this field have led to small cutting and welding torches and high intensity light sources. Other possible applications for these smallest of all arc-plasma units involve the handling of ceramic materials, use in the seeding of a larger plasma jet used in chemical synthesis, etc. In this section we divert slightly from strict industrial application and discuss the application of arc-plasma units in the exclusive context of NASA's space program.

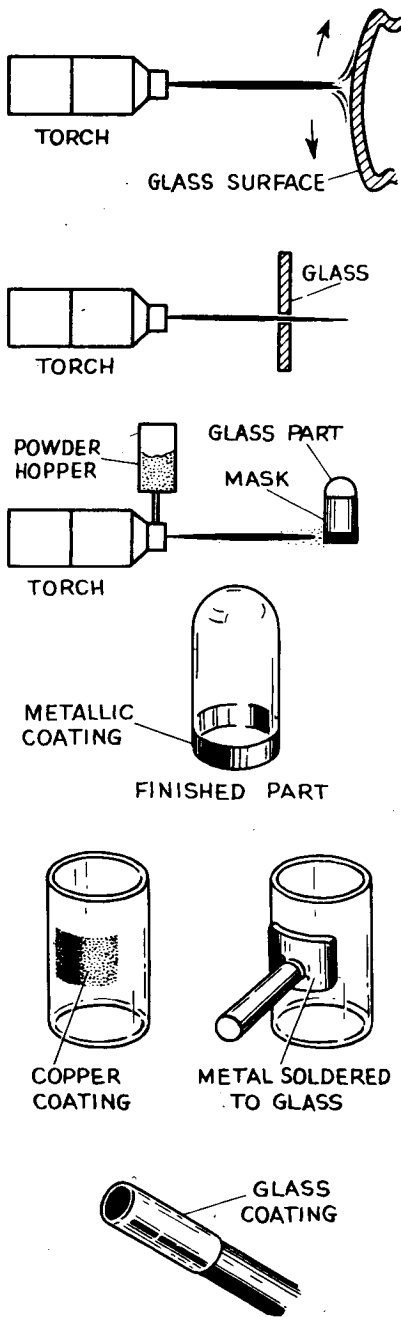


FIGURE 2.25.—Uses for plasma jet in the glass industry.

Courtesy of Thermal Dynamics Corporation

ARC THRUSTER PROGRAM

In 1958 and 1959 arc-propulsion contracts were initiated and supervised by personnel at the Army Ballistic Missile Agency. After the staff, which had worked on arc-engines, transferred to the Marshall Space Flight Center, the 1-kw. arc-engine development and supporting contracts were undertaken to produce engine packages for use in attitude and position control of spacecraft. Specifically in the electric propulsion engines, the arc-jet has the highest thrust-to-weight ratio and thus fulfills a vital role in this family of engines. Because nuclear power supplies are not yet available and a need exists for the engine function, adaptability to present battery (with solar cell recharge capability) supply was considered essential. In addition to contract effort, work was done on attitude control techniques, and suitability for various missions was also examined. Following the preliminary work of trying to delineate the area of possibility for extended life use, a major contract toward flight hardware was begun. Various aspects were examined in supporting research, nozzle flow phenomena and cryogenic feed systems among others. As the work progressed, a flight test was planned. In conjunction with this effort, RF-generation characteristics measurement was conducted from 30 cycles to 10 kilomegacycles in August of 1961.

The program was to develop flight models, flight test them, and perform analysis and evaluation of the results. The purpose of the 0.01 pound arc-engine project was to develop reliable arc-engines requiring approximately 1-kw. power for attitude and position control of spacecraft. The engine was designed to be capable of operating continuously for a period of at least 90 days at a thrust level of 0.01 lb. minimum when powered by a 1-kw. source. Compatibility with a 2,000 cycle, two or three phase 110 volt basic power supply was desired, together with minimum transformer or rectifier requirements. The weight and volume of the engine system were to be the minimum consistent with reliability and long life. Specific impulse of the system (defined as the average thrust level divided by the total flow rate of fluid to the engine) was to be in the range of 1,000-1,500 seconds and to be constant within 10 percent during the 90-day operating period. Total time in space might be two years.

Power supply limitations dictated the necessity for a small unit (1-kw. or about 0.015 lb. thrust) and required times (several months to years) eliminated the feasibility of using air bottles or small chemical rockets. Specific impulse of about 1,000 or better (with high thrust to weight ratio), fail safe capability of good specific impulse if power failure occurred, and a number of small units (so that failure of one unit does not negate the whole system) made the electric arc-

jet the logical choice. Low cost experimental units and excellent probability of early success complete the picture of the 1-kw. unit.

In the process of the NASA work on electrical thrust devices for propulsion, a generalized vehicle performance analysis was conducted (Reference 73, Chapter 7). The relationship among payload ratio, characteristic velocity, operating time, power source weight, and "optimum" specific impulse was obtained. The "optimum" specific impulse was shown to be mainly a function of operating time and power source specific weight, with a minor dependence on characteristic velocity. Thus, the most useful region of operation of an electric thrust device can be expressed in these terms.

The most immediate and promising use for electric arc propulsion systems was shown to be in satellite attitude and orbit control and in orbit modification. In these applications the electric arc, at a specific impulse of about 1,000 seconds, provides a reduction in propellant weight of an order of magnitude over conventional bottled gas or monopropellant systems.

Preliminary engineering evaluations of several types of advanced space propulsion systems were made by NASA to include application of advanced propulsion systems and components. A critical evaluation of thrust generators, primarily electrical, was made on the basis of their current performance and future potential in relation to complete systems. The results of a survey of promising electrical power sources and the problems involved in the application of fusion power to propulsion were also presented as were the results of studies of controllable satellite propulsion systems. A preliminary analysis of a nuclear turboelectric plasma-jet system was presented and it included a study of mission applications of immediate interest. A preliminary evaluation of the electrical ramjet showed the reasons for generally limited applicability for this type of power plant. Recommendations for electrical power plant component development were made.

As a part of NASA's program of investigation of low-thrust plasma propulsion devices (Reference 203, Chapter 7), the initial effort was directed toward the development of a small thruster (approximately 0.03 pound thrust) which would be capable of operating with a specific impulse above 1,000 seconds and with good power conversion efficiency.

Under NASA auspices (Reference 209 and 73, Chapter 7) an analytical and experimental program based on objectives of flight testing and the design considerations of a 1-kw. plasma-jet flight test engine was developed. The engine was to be ultimately suitable for attitude/orbit control of spacecraft and was to be used in the 1965 period. The relationship of the flight test engine design philosophy, to the final attitude/orbit control system was discussed. The choices of

propellant, storage, feed system, as well as the electric power adaption and starting system were treated.

Hydrogen and ammonia propellants were compared as a function of mission time using the then-current technology. The benefits of supercritical hydrogen storage in the small sizes and the general lack of zero gravity feed problems were discussed. The flight test engine storage and feed system was described. Recent advances in efficient power adaptation of an arc to power source using constant current controls were reported. A new, simple technique for experimentally making over 7,000 consecutive successful starts without noticeable erosion was described.

The major significance of this work was the demonstration of a hot-wall thruster design showing that the cooling system can be eliminated and that better efficiencies result from the use of designs of this type. In early 1961, it was shown to be possible to obtain over 50 percent efficiency, greater than 1,000 seconds specific impulse using hydrogen in the hot-wall thruster (Reference 203, Chapter 7). The modified configuration appears to give a relatively uniform exhaust and good operating stability and allows some recovery of dissociation energy.

In the fall of 1960, NASA Headquarters awarded 12-month contracts to AVCO (for dc systems) and to the General Electric Company (for ac systems) for the development of 30-kw. arc-engines. In July 1961, a decision was made to continue the dc efforts and reduce the level of effort on ac systems. These engines were to be used with high power SNAP-8 electric power sources and for missions such as orbital transfer in cislunar space, lunar supply, supply missions between manned space stations, and others requiring up to approximately 1 pound thrust at a specific impulse of 1,000.

ELECTROTHERMAL PROPULSION

A theoretical analysis of the effects and limitations of regenerative and radiation cooling began at NASA's Lewis Research Center in 1959. The results of this work have demonstrated that the upper time limit of operation for a regeneratively cooled hydrogen engine is about 1,500 seconds.

It was shown that when using hydrogen, regenerative cooling is superior at the thrust levels considered. Test of a 30-kw. hydrogen arc jet has demonstrated that it may be cooled regeneratively or by radiation at a specific impulse of 1,000 seconds and at the thrust levels of interest. However, engine efficiencies considerably higher than the best values reported to date are required. Recently, the change in thruster performance due to regenerative cooling has been considered for a frozen hydrogen flow. It was demonstrated that the gains to

be achieved are strongly dependent on operating conditions. For example, operation at a specific impulse of 1,000 seconds produces very small performance gains with complete regenerative cooling.

In 1959 theoretical studies were conducted on the performance of various propellants for electrothermal jet engines. In one work, eight propellants were considered, and of these propellants hydrogen and helium appear to be best for specific impulses in the vicinity of 1,000 seconds. Above 1,600 seconds, lithium is more efficient. A direct outgrowth of the analysis was the conceptual design of a resistance-heated hydrogen rocket (resistojet).

The theoretical performance of hydrogen and a number of non-cryogenic gases has been evaluated and some operating and mission problems have been observed.

A research model of a resistojet incorporating an electrically heated tungsten tube has been evaluated in order to better understand its operation and performance. The research model has demonstrated the feasibility and some advantages of this type of engine. However, since the particular model was water-cooled, it failed to yield high gas heating efficiencies. As a result, new engine designs are now being tested with emphasis on higher efficiencies, longer life, reliability, and a specific impulse of approximately 1,000 seconds (theoretical limit is approximately 1,100 seconds). One of the newest designs utilizes an electrically heated tungsten wire helix and radiation cooling.

The usual performance analysis of an electrothermal engine is based on the assumption that the flow process is one-dimensional; however, in actuality, the flow is not adiabatic, and often the nozzle flow has a severe enthalpy profile associated with it. This type of profile of course negates the one-dimensional assumption and can have a pronounced effect on the performance. An analysis of the effects of certain nonuniform flows on the performance of electrothermal thrusters has been performed. Performance characteristics have been recorded for uniform specific impulses ranging from 1,000 to 2,000 seconds for pressures from 0.01 to 100 atmospheres and for engine wall temperatures of 500° to 3,000° K. The nonuniform profile changes the uniform specific impulse by 11 percent at most, and the change can be either helpful or detrimental to engine performance depending upon the specific operating conditions. In general, increasing the engine wall temperature causes the specific impulse to approach the uniform flow value.

Economic Impact of Plasma Technology

RESEARCH

In an attempt to define the state-of-the-art of plasma jet technology, the National Academy of Sciences, Materials Advisory Board ¹ summarized their findings in a 1960 review of plasma technology. The report containing their findings on the development and possible applications of plasma and related high-temperature generating devices served as the springboard for a monograph on plasma-arc technology—this work.

An attempt has been made to update certain data which, it is hoped, will provide a clearer picture of the current trend in both research and industry. Tables 3-I, 3-II, and 3-III are compilations to this end.

TABLE 3-I.—*High Temperature Research, Development, and Testing Expenditures*

Agency	Number of Projects	Annual Expenditures 1960
Air Force.....	50	\$6, 500, 000
Other Armed Services.....	25	1, 200, 000
Atomic Energy Commission.....	5	5, 500, 000
NASA.....	10	11, 100, 000
National Science Foundation.....	6	700, 000
U.S. Bureau of Mines.....	1	25, 000
National Bureau of Standards.....	1	950, 000
Total Government	-----	25, 975, 000
Universities.....	20	400, 000
Industry.....	15	1, 800, 000
Grand Total	-----	28, 175, 000

¹“Development and Possible Applications of Plasma and Related High-Temperature Generating Devices.” Report MAB-167-M Division of Engineering and Industrial Research, National Academy of Science, National Research Council, Washington, D.C. (August 30, 1960).

TABLE 3-II.—*High Temperature Research, Development, and Testing Expenditures*

Typical Distribution of Expenditures

Subject	Number of Establishments	Annual Expenditures
Development of Generator.....	15	\$600, 000
Properties of High Temperature Gases.....	35	1, 500, 000
Gas Dynamics.....	25	1, 000, 000
Magnetohydrodynamics.....	25	1, 000, 000
Materials Testing and Behavior.....	20	1, 000, 000
Wind Tunnels.....	15	2, 750, 000
Chemical Synthesis and Extractive Metallurgy.....	27	1, 550, 000
Refractories and Ceramics.....	10	400, 000
Crystal Growth.....	10	100, 000
Spray Coating and Compacts.....	15	500, 000
Propulsion Systems.....	10	11, 000, 000
Thermonuclear Power.....	5	7, 000, 000
Electronics.....	10	1, 000, 000
Grand Total.....		29, 400, 000

TABLE 3-III.—*Typical Industrial Outgrowths of High Temperature Research and Development Expenditures*

Product	Number of Companies	Gross Sales per Year
Plasma Generators for Research and Development and Welding Cutting.....	7	\$3, 500, 000
Furnaces—Electron Beam, Vacuum.....	10	10, 000, 000
Advanced Materials—Tungsten, Graphite, Plastics.....	20	75, 000, 000
Chemical Synthesis.....	4	5, 000, 000
Flame Spraying.....	8	5, 000, 000
Crystal Growth.....	10	5, 000, 000
Grand Total.....		103, 500, 000

COMMERCIAL MARKET POTENTIAL

Judging by the results obtained in direct correspondence with industrial organizations known to be investigating commercial processes, a sizable portion of current work is considered proprietary. In equipment design the same feeling can be found to prevail, and it is really not surprising when one considers that only a few industries are actually involved.

According to a survey made in 1963, at least six companies in the United States were offering plasma torches and auxiliary equipment for sale, and possibly as many as twenty were working on designs of generators for special purposes. The companies making and selling torches were:

AVCO Corporation, Industrial Products Subdivision:

Lowell Industrial Park

Lowell, Massachusetts

Linde Company:

(Division of Union Carbide Corporation)

New York, New York

Metallizing Engineering Company:

Westbury, Long Island, New York

Plasmadyne Corporation:

Santa Ana, California

TAFA:

(Division of Humphreys Corporation)

180 North Main Street

Concord, New Hampshire

Thermal Dynamics Corporation:

Lebanon, New Hampshire

An estimate of the market potential created by plasma technology through 1967 is given in Table 3-IV. Most of the commercial equipment presently marketed is designed for welding, cutting, flame coating, or research purposes. No company manufactures a reactor specifically for chemical synthesis. However, Plasmadyne and Thermal Dynamics are promoting the sale of equipment for chemical-processing purposes and are supplying information on adaption of equipment for specific reactions.

TABLE 3-IV.—*Market Estimates*

Market	1963 Sales	1965 Sales	1967 Sales
Plasma Arc Cutting.....	\$400, 000	\$500, 000	\$700, 000
Welding.....	50, 000	100, 000	200, 000
Flame Spraying.....	300, 000	400, 000	600, 000
Wind Tunnel Heating.....	600, 000	1, 000, 000	2, 000, 000
Small Research and Development Systems.....	400, 000	400, 000	400, 000
Hard Facing with Transferred Arc.....	50, 000	100, 000	200, 000

NASA and Plasma-Arc Technology

PLASMA JET—WHY NASA IS INVOLVED

The nature of the total environment in which space vehicle systems must operate is becoming increasingly well understood. If we are to build systems sufficiently reliable to cruise in space for extended periods of time, land on the moon, and return through the atmosphere, it is necessary that there be available on earth the capacity to duplicate the space and reentry environments as closely as possible. Such ground facilities will provide a basic understanding of the design problems associated with the environments and lead to systems of increased efficiency and reliability.

The technical and technological areas where increased knowledge is required because of the new aspects surrounding space travel are four in number: (1) medical areas including personnel acclimation and psychological and attitude orientation, (2) electronic areas involving new concepts of circuitry and communications, (3) guidance control and propulsion involving electric thrusters, and (4) materials areas involving such fields as fuels and propellants, and materials of construction.

Within the fourth area of effort lies the space-simulation work with the plasma arc. Of prime importance in this effort is the testing of materials to determine their suitability for the hostile environment of space. Above all, the material must be able to withstand the rigors of reentry.

MATERIALS TESTING

One of the most critical design aspects surrounds the design of the heat shield to protect a space capsule against the heat generated by its high speed entry into the dense atmosphere of the earth. In order to bring excursion times into the realm of reason, it is necessary to consider reentry velocities from about 40,000 to about 100,000 feet per second for future vehicles. Our current space vehicles range in reentry speed up to 36,000 feet per second for the Apollo. The speed of 36,000 feet per second corresponds to energy levels of around 27,000

Btu per pound, which is 5 to 10 times the amount of heat per pound that can be absorbed by the best currently used heat shield materials.

The survival of our current designs, then, depends upon the fact that only a minor fraction of the total heat generated is actually transferred to a blunt-shaped vehicle. The rest appears as atmospheric heating through the action of shock waves, radiation, etc.

The survival limit of velocity for natural meteorites is about 55,000 feet per second—man will have to make large improvements to exceed this limit if he is to survive at a reentry speed of 100,000 feet per second. It is in the realm of materials development and testing, to help man survive high speed reentry, that the plasma jet may realize its greatest application in materials investigation. As an example, for the Mercury and Apollo spacecraft at reentry, total enthalpies in excess of 10,000 Btu per pound and total pressures in excess of 10,000 atmospheres can occur simultaneously at Mach numbers in excess of 20. As a result of these severe requirements, designers turned to short-duration "hot-shot" and shock-heated wind tunnels to alleviate some of the problems of containing and expanding high-enthalpy, high-pressure air. Real air flows at high Mach number can be simulated in these facilities, but the short test duration creates difficult instrumentation problems. The desire to increase the flow time under high enthalpy conditions was one objective of NASA efforts to develop high capacity heat sources for its hypersonic wind tunnels.

Equally important, however, is the need to provide high capacity heat sources to prevent liquefaction of air when it is expanded at the high pressure ratios required to reach Mach numbers in the order of 20. It is felt by many that in order to simulate reentry conditions on the ground adequately, NASA will some day need a plasma-jet activated tunnel into which an entire space capsule can be placed and in which the entire reentry can be accurately simulated in terms of temperature, pressure, and duration.

A discussion of materials testing was given in Chapter 2.

PLASMA-JET PROPULSION

As the age of space flight began to be realized, aerospace scientists and engineers began to recognize more fully the need for highly efficient specialized propulsion devices designed and optimized only for operation in space in order to provide adequate on-board propulsion capability. The conventional large chemical combustion rockets, which had originally been developed for missile applications, were well suited to operating within the earth's atmosphere, and their advanced development status and thrust-to-weight ratios provided the necessary capability for launching space vehicles from the ground.

Smaller versions of the chemical combustion rocket engines were also being developed for on-board propulsive applications on vehicles operating in space. But their rates of propellant consumption were high, and the resulting launch weight penalties seriously limited the duration, performance, and distance which could be achieved in many space missions.

In principle, it was known that there were several types of unconventional propulsion devices which could be designed to operate in the space environment with far lower rates of propellant consumption than the chemical rockets, and that these devices, if developed, could potentially provide greatly superior mission capability for many space vehicles, even though they could not be used for launching the vehicles from the ground. Among the most promising of these unconventional propulsion devices were the electrical rocket engines, some of which are ramifications of the plasma jet. Such propulsion devices led a number of industrial and government laboratories, largely under the sponsorship of the Department of Defense and NASA, to carry out extensive research and development work on several versions of the electrical rocket concept.

It was shown that at least three fundamentally different principles can be employed to produce thrust from a combination of electrical power and propellant flow in an electrical rocket propulsion device. The three general types of engines are:

1. *Electrothermal propulsion engines*, in which thrust is produced by heating a propellant gas to a very high temperature by means of some electrical heating device (for example, a solid resistance heating element or an electric arc) in a thruster chamber, then thermodynamically expanding the heated gas in a divergent nozzle to accelerate it to a high supersonic velocity, and discharging the high velocity gas in one direction from the nozzle exit.
2. *Electromagnetic propulsion engines*, in which thrust is produced by electrically transforming a flowing propellant into its plasma (ionized) state and then generating an electromagnetic field which acts to accelerate the charged plasma particles to very high velocity.
3. *Electrostatic propulsion engines*, commonly called ion propulsion engines, in which thrust is produced by stripping electrons from neutral atoms in a flowing propellant to produce positive ions, and then accelerating the positive ions by means of an electrostatic field to produce a very high velocity ion beam which is discharged from the engine. It is necessary, however to neutralize the positively charged ion beam by injecting

electrons at the exit in order to prevent charge accumulation and thrust cancellation. Another type of electrostatic propulsion involves acceleration of charged colloidal particles in a similar manner.

All three categories of engines have the following characteristics in common :

- a. Electric power is employed to accelerate a propellant to very high velocity in order to produce thrust.
- b. Low thrust levels are produced which are suitable only for space propulsion.
- c. Rates of propellant consumption per pound of thrust produced are relatively low.
- d. Power input requirements per pound of thrust produced are relatively high.

Characteristic (c) is advantageous because it minimizes the amount of propellant which must be carried for a given mission, but characteristic (d) is disadvantageous because it indicates the need for a sizable electric power supply on board in order to produce the required thrust.

The various categories of electrical rocket engines differ in the magnitudes of characteristics (c) and (d). Electrothermal engines—of which the arc-jet is one type—tend to have a somewhat higher rate of propellant consumption and a higher thrust-to-engine-weight ratio compared to the other categories.

(Specific work in the propulsion category was discussed in Chapter 2.)

NASA'S CONTRIBUTIONS

Without the impetus provided by the National Aeronautics and Space Administration and its predecessor—National Advisory Committee for Aeronautics and other government agencies—indeed, without the American manned space-flight effort as a whole—the science of plasma arc and the accompanying technologies would not have advanced nearly as rapidly as they have. NASA became particularly active in plasma arc technology late in 1957 and since then has engaged in research and development in plasma arc technology to develop our manned space flight effort to a fine pitch.

Included here is a compilation of plasma arc work done at the four NASA research centers which have pursued programs in this field. Comprised of published articles, major speeches and contract results, it presents a picture of only NASA activities. For the full picture of plasma arc work, to this must be added Air Force contributions (many NASA contracts were based on cooperative subdivision of overall

areas of interest to avoid duplication), additional Army and Navy research and, of course, the large amount of private industrial work. Some of the latter may eventually lead to contract reporting, some to commercial products, and some to published research papers. A considerable portion, however, remains in proprietary files.

In compiling the summary of each of the centers, there has been no attempt to identify the interchange of information between Ames, Langley, Lewis, and Marshall throughout the development program.

AMES RESEARCH CENTER (NASA)

A modest initial investigation was begun in 1956 with pressure-liquid constricted arcs of the Finklenberg-Maecker-Gerdian types using high pressure water as the constricting and cooling medium. Later, liquid air was employed in the hope that the products of vaporization would be suitable for aerodynamic research purposes. Arcs of this type were found unsuitable because of the difficulty of preventing gas contamination caused by electrode burning.

In 1958 the need for wind-tunnel arc heaters became a matter of increased urgency as it became apparent that new facilities would be needed to solve the aerodynamic and heating problems of reentry vehicles. The requirement set up at that time was an electric-arc heater capable of operating continuously on uncontaminated air at pressures to 100 atmospheres, supplying 14,000 Btu per pound with a power input of 1 megawatt. However, a survey of the market revealed that the best available off-the-shelf hardware would only supply less than 100 kilowatts, at 2,000 Btu per pound, to an inert gas at 1 atmosphere pressure. An in-house effort was initiated to assess further the state-of-the-art and to conduct basic experiments to improve it. Electrical engineers, aerodynamicists, and thermodynamicists worked closely in the ensuing years, first to rediscover some of the arc technology which had been lost in history; then to perform experiments and analyses to extend the technology and provide basic data on which to design more advanced equipment, and finally to focus this knowledge on the design and development of specific arc heaters to be used in Ames facilities.

Experiments and theoretical analyses which eventually led to the development of the Ames concentric-ring arc heater were begun in 1958 (Figures 4.1, 4.2, and 4.3). The basic problem was to develop electrodes capable of operating at high power in an oxidizing atmosphere. This requirement led to many experiments with magnetically rotated arcs to spread the heat load over the electrodes, thereby preventing their deterioration and excessive contamination of the effluent jet. The electrical industry had used this technique for circuit breakers, and the magnetic drive had been used on the Berkeland-Eyde arc heater

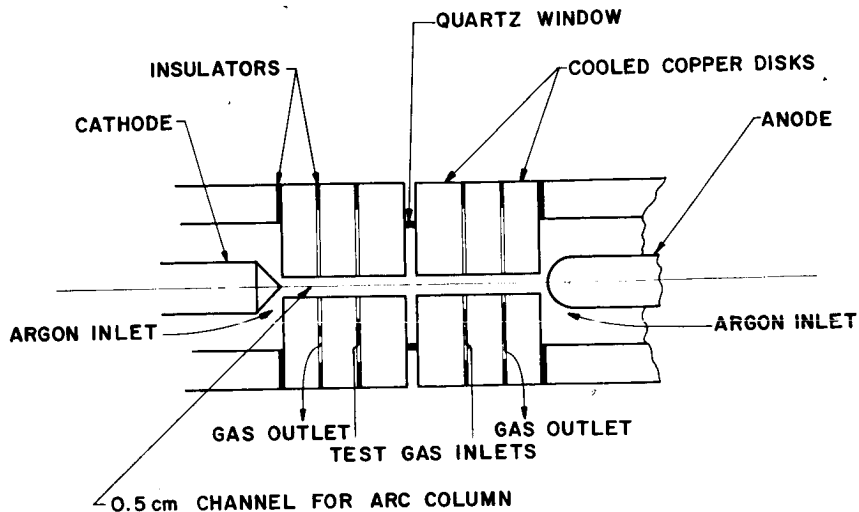


FIGURE 4.1.—Constricted arc plasma source.

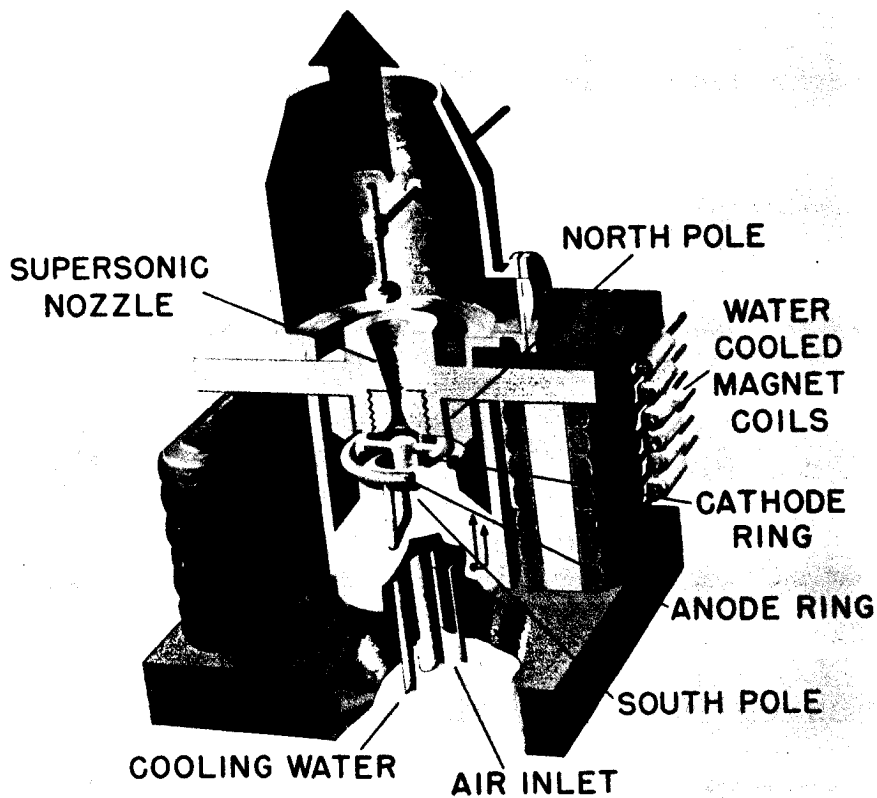


FIGURE 4.2.—Ames concentric ring arc jet.

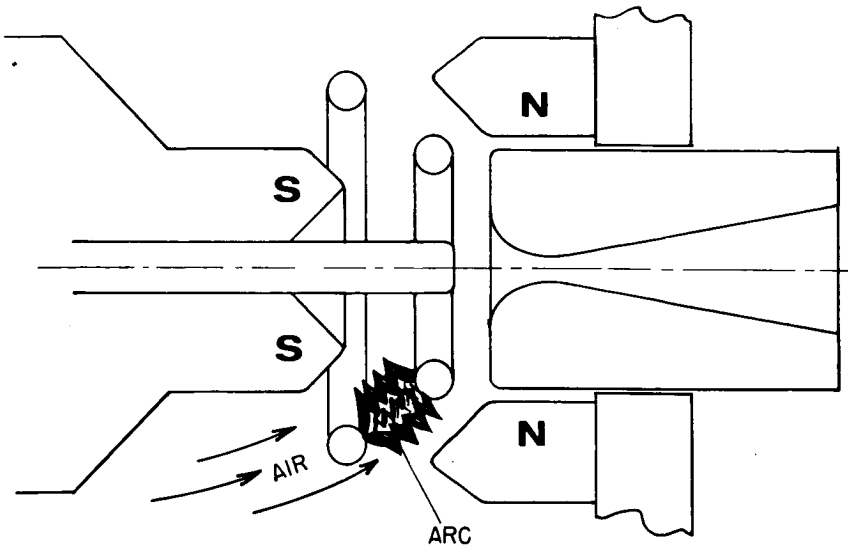


FIGURE 4.3.—Ames concentric-ring unit.

around the year 1900; so the idea was not new. On the other hand such technology as existed on magnetically driven arcs of that day appeared to be lost in history, and there was an almost complete lack of general data for design purposes, especially at high pressures. By early 1960, at least two successful arc heaters had been developed and tested. These heaters used the water-cooled, concentric-ring electrode configuration with crossed-magnetic field to rotate the arc, thereby allowing high current capacity. One of these heaters had been operated with air at 1 megawatt input, 100 atmospheres pressure, and approximately 1,500 Btu per pound. At pressures less than an atmosphere, enthalpies of about 9,000 Btu per pound had been obtained.

Perhaps of greater importance, however, was the basic information obtained for use in the design of later units. At various power levels enthalpy was determined for a range of pressures from about 0.1 atmosphere to 100 atmospheres. Parametric variations of operating conditions provided data on the variation of arc voltage with pressure and field strength, the effect of arc-chamber pressure on arc velocity of rotation over the electrode, the effects of current and field on arc velocity, and the effect of arc velocity on maximum permissible current with thin-wall, water-cooled, copper electrodes of several wall thicknesses.

The decrease in arc rotational velocity with increasing arc chamber pressure or decreasing field strength was satisfactorily explained by a concept based on the idea that the arc acts as though it were a solid

aerodynamic body having drag. The arc is driven by the electromagnetic force of the field and the resulting equilibrium velocity is that velocity at which the drag force on the arc equals the electromagnetic driving force. The effect of decreasing arc velocity with increasing pressure is caused by the increased drag on the arc.

In April 1960, while development of the concentric-ring arc heater was continuing, a new concept was proposed for a 3-phase, ac arc heater. A feature of this 3-phase arc heater is that it behaves like a resistive load and does not require large harmonic correction to satisfy power company requirements, a feature of economic importance for industrial applications. In this respect, it differed from all other 3-phase arc heaters described in the literature. Although experiments have demonstrated the concept and the possibility of efficient 3-phase ac arc heaters, development remains to be done to produce a device having practical application.

In 1961, while development continued on the Ames concentric-ring arc heater, a program was launched for the design and construction of constricted-arc heaters (Figure 4.4). Motivation for this effort was the need to improve the heat transfer between the arc and the gas as a means of increasing the enthalpy. Here again, the idea of arc constriction was not new. The Germans utilized arc constriction in about 1920, restricting the arc by water flow.

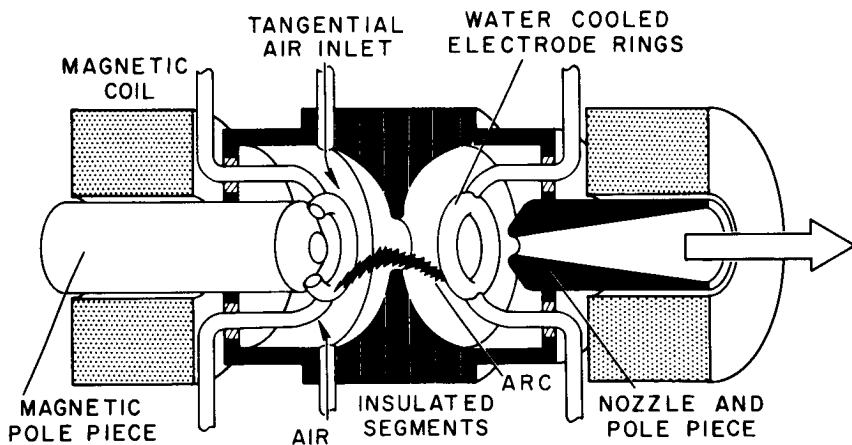


FIGURE 4.4.—Constricted arc heater.

Courtesy of Ames Research Center

Some work was being done in industry with constricted arcs, but little information was available in the literature. Stine and Watson had developed a theory for the analysis of a direct-current electric arc with air in steady flow along its axis. Typical numbers from

these experiments showed that with arc heater operating at a pressure of about 7 atmospheres absolute and 0.1 pound of air per second, the constrictor increased the enthalpy of the air from 3,500 Btu per pound to 12,000 Btu per pound and the power input from 1 megawatt to 2.5 megawatts. The results bore out the qualitative predictions of theory. More advanced work has been done with constricted arcs, but the results have not yet been published. These later experiments have been directed toward increasing the length of the constrictor in relation to its diameter and improving the constrictor shape and construction to reduce the tendency of the arc to short-out on the constrictor.

An advanced arc-heater, which further exploits the theory of Stine and Watson, is under development at Ames. This device will be known as the Supersonic-Arc Plasma-Jet (Figure 4.5). This new concept in arc-heater design offers the possibility of a step improvement in the enthalpy that can be recovered in the gas. In this type of arc heater, the arc is constricted to the maximum amount by passing it through the sonic throat and on through the supersonic jet to the anode. The hot tungsten cathode is located upstream of the sonic throat in a moderate-pressure nitrogen environment. Oxygen-rich gas may be admitted downstream ahead of the sonic throat to simulate atmospheres of the earth or other planets. In operation, an auxiliary arc is initiated in the nitrogen environment as a source of electrons, and the arc is transferred through the sonic throat, then on into the high-velocity, low-pressure region to the anode. Diffusion of the arc, by virtue of the low pressure, controls heating on the anode. A pilot model has been operated, and enthalpies in excess of 30,000 Btu per pound have been measured. The concept has been applied to the design of larger apparatus and initial runs are in progress.

The results of Ames' efforts in the field of electric-arc technology may be broadly identified as follows:

1. Advanced arc-heater facilities.
2. Contributions to the theoretical understanding of various types of arc heaters over a range of operating conditions, pointing the way to improve designs, some of which are currently being pursued at Ames.
3. Critical evaluation of the available methods for measuring arc-heater performance for various designs and operating conditions.
4. New instrumentation and refined techniques for acquiring the data needed to evaluate arc-heater performance.

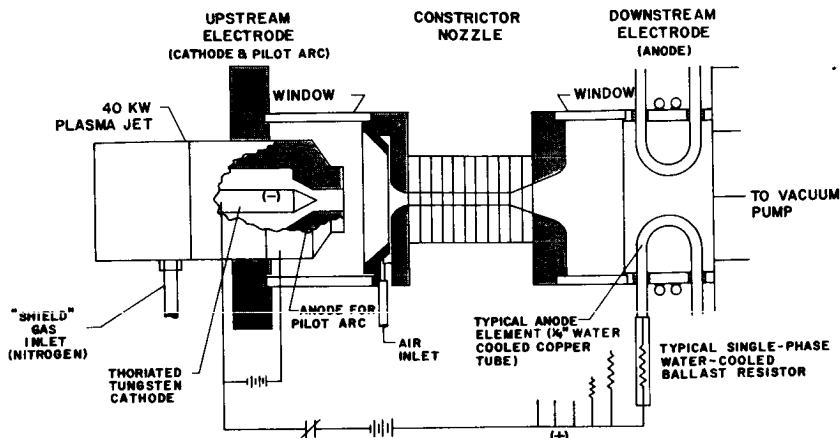


FIGURE 4.5.—Ames supersonic-arc plasma-jet.

LANGLEY RESEARCH CENTER (NASA)

Development of electric arc-powered devices was started at the Langley Research Center in the latter part of 1956. The first several devices were water-stabilized arc jets. Because research for flight vehicles required a high-temperature stream of air rather than evaporated water, a transition through liquid nitrogen and liquid air resulted in the first gaseous-air electric arc jet in March 1957. This is believed to be the first electric arc-powered facility which directly heated gaseous air for the purpose of producing a high-temperature stream in which materials research was performed.

Generally, early arc-powered devices possessed two serious deficiencies: contamination of the stream was high and running time was short. For example, in early arc-heated jets contamination of the airstream by carbon from the electrodes exceeded 20 percent in some instances, and running time was measured in seconds. Although this running time was many orders of magnitude greater than the microseconds of testing time available in shock tubes, the time was nevertheless too short for many desired research uses. Intensive development of electric arc-heating devices was initiated to remove the two deficiencies mentioned and to seek other improvements, including operation of arcs at high pressure and at high power inputs. Many configurations of electrodes and arc chambers were studied and improved electric-arc air-heating devices were built and operated. The contamination has been steadily reduced from values in excess of 20 percent to very small fractions of a percent, and running times have been increased to such an extent that the arc facilities may be designated as continuous. The decrease of contamination is achieved by the

replacement of graphite electrodes (which are eroded rapidly by the arcs and the high-temperature air) with water-cooled copper electrodes which experience very little erosion.

The potential usefulness of electric arc heating of air to simulate the high-temperature environment of hypersonic flight and of reentry was recognized early. In 1957 funds were requested for the construction of a 10-megawatt arc tunnel (as shown in Figure 4.6). The design of the electric arc chamber, which is the heart of the arc tunnel, was finalized in March 1959, on the basis of the best information then available on electric arc heating of air, and included some daring extrapolations as to the size and power of arc facilities which could be successfully developed.

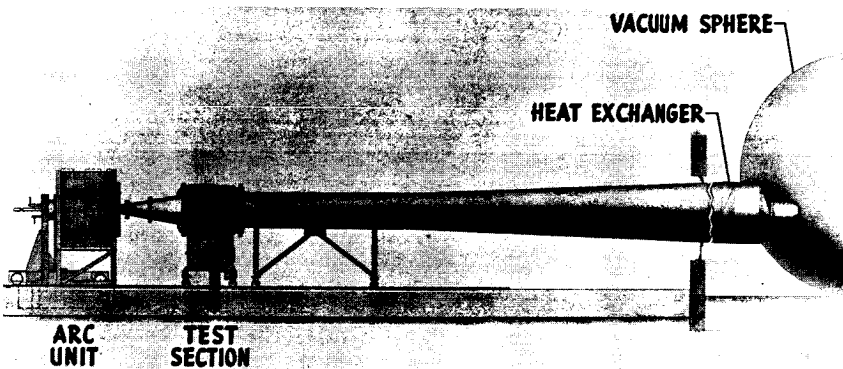


FIGURE 4.6.—10 megawatt arc tunnel.

Courtesy of Langley Research Center

The design of this arc unit was based on the use of alternating-current power distributed to multiple electrodes. This configuration was chosen because of the ready availability of alternating-current power in large quantities and because alternating-current arc units had been developed in much larger sizes than had those employing direct-current. However, because of rapid advances both in performance requirements and in arc technology, the original design became outmoded before it became fully operational. Current design changes envision performance requirements compatible with the very latest advancements in the state-of-the-art.

Arc-heater development work is actively being conducted at Langley and a promising design has been conceived and built. Testing the heater with this new design should commence shortly. The new design combines some of the best features of two schools of thought in

arc-heater design. The main arc is struck between two tandem cylinders with a constrictor section between. An intense magnetic field (10,000 to 15,000 gauss) rotates the ends of the arc where it attaches to the electrodes. This essentially diffuses the arc at these points. In addition, the air flows parallel to the arc over most of its length. This provides good heat-transfer characteristics from the arc to the air and results in an efficient arc heater. In this design an auxiliary arc might also be used to preheat the air before it reaches the main arc.

A new dc arc-heated wind tunnel (20-inch HAHT) is being put into operation, and check-out tests are being conducted to determine the operational test range. The arc operates at pressures up to about 68 atmospheres with currents up to 3,000 amperes. The arc heater was designed for 2 megawatts of power. Aerodynamic tests were scheduled to begin this year. The nozzle makes use of a $7\frac{1}{2}^\circ$ (half angle) cone expanding the flow to a Mach number of 13.5.

A small hypersonic tunnel with a 3-inch test section has been modified to a tunnel with a 1-foot test section. The modification was made possible by the acquisition of a new five-stage steam ejector. The arc heater of the former tunnel is being used with a 1-foot tunnel; however, the available dc power supply has also been recently increased from 900-kw. to about 1,500-kw. This arc heater is of the type which uses an intense magnetic field (12,000 to 15,000 gauss) to rotate the arc. The arc is struck between a cylindrical outer electrode and a doughnut-shaped inner electrode. The limits to which this arc heater can be operated from the standpoint of maximum pressure and maximum power input have not been explored. The available 500 psi air storage and 900-kw. power supply have been fully utilized without failure of the arc heater.

In many ways this small hypersonic tunnel was used as a pilot model for the hyperthermal leg of the hypersonic aerothermal dynamics facility, a new facility which uses an arc heater for the hypersonic tunnel. The heater is designed for stagnation pressures as high as 3,000 psi. The arc is struck between two doughnut-shaped electrodes and rotated by a magnetic field. The heater is on site but shake-down tests have not yet commenced.

A major use of the arc heater at Langley has been as a plasma generator. The arc heater will produce temperatures high enough to ionize alkali metals which are used in the plasma accelerator.

LEWIS RESEARCH CENTER (NASA)

Work at Lewis Research Center in the general field of electrode research and development began in 1957 with the intent of obtaining an

arc chamber capable of supplying 200-kw. to air at atmospheric pressure levels.

In 1958 a major step toward the accomplishment of this goal resulted when magnetic fields were employed in chamber designs. Nearly an order of magnitude increase in power level was achieved along with reduced electrode erosion rates and improved arc stability. An outgrowth of this work was an arc chamber which was used to power an arc tunnel having the following characteristics:

Volts	240
Amps	2100
Stagnation pressure atm.....	2.0
Mass flow, lb./sec.....	2.0×10^{-2}
Nozzle throat diameter, inches.....	0.5
Stagnation enthalpy (energy balance)	
Btu/lb.	10,000
Run duration.....	Continuous

Early in 1959, the specifications for a 1.5 megawatt arc tunnel were established. This continuous operation tunnel was designed for large scale satellite reentry heat transfer studies and associated areas of research.

Research on the magnetically spun type of arc continued, and the range of operation and the effects on performance resulting from the independent variation of operating parameters were investigated. The results of this work indicated that low enthalpy high-pressure operation in the 1.5 megawatt arc tunnel may be difficult to attain in view of the low voltage power supply. Operation may be confined to the high-enthalpy, low pressure conditions approaching those listed in the specifications.

In the fall of 1959, a commercial arc chamber was tested using a 550 volt, 6,000 amp dc power supply. A strong gas vortex was used to stabilize the arc in this configuration. Although many problems were encountered during the first series of tests, the results proved enlightening and encouraging. A power level approaching 1 megawatt was obtained for a period of about 10 seconds.

A modified version of the aforementioned commercial arc chamber and an arc chamber developed in-house are considered the most promising for powering the 1.5 megawatt arc tunnel. The in-house heater, which will initially power the tunnel, consists of four sets of electrodes connected to a common plenum. Each set of electrodes incorporates a magnetic field to rotate the arc. Although multiple electrode coupling has not been explored to an appreciable extent at Lewis, other research organizations such as General Electric and Avco have elucidated many of the problems and confirmed the operation of this type of electrode system. The commercial arc chamber will serve as a

substitute heater for the arc tunnel, and eventually it may be advantageous to power the tunnel with two of these arc chambers in parallel.

Many of the problems associated with the production and nature of low density hypersonic argon and nitrogen jets were studied in a 10-kw. arc powered facility. For instance, pressures and enthalpies in the Mach 4 jet were mapped and enthalpy comparisons were performed from stagnation point heat transfer measurements and energy balance computations. In addition, an analysis was made of the change in the energy state of nitrogen as it flows from the arc heater to the low-density test section.

A series of magnetohydrodynamic (MHD) experiments is now under way in a 200-kw. arc tunnel. A magnetically spun dc arc is used to heat argon to stagnation enthalpy levels of 3,500 Btu/lb. at 0.5 atmosphere. Provisions are included for "seeding" the argon which serves as the working fluid. Lithium, with low enthalpy of ionization, is a typical seeding material for the following experimental program:

1. Magnetic nozzle development—an attempt has been made to measure the reaction force on a single turn coil due to the interaction of the applied field with the induced azimuthal current field. Photographic studies were initiated to observe some of the fluid-flow properties of the gas during confinement.
2. Conductivity measurement—measuring the electrical conductivity of seeded and unseeded argon plasma, and studying of nonequilibrium effects.
3. MHD power generation—utilizing the arc-heated argon as a fluid medium for space power generation studies.

(Work concerning the Plasma Jet Propulsion Program undertaken by Lewis was discussed in Chapter 2.)

MARSHALL SPACE FLIGHT CENTER (MSFC-NASA)

At MSFC investigations with the plasma arc have been concentrated in four areas of endeavor: plasma physics, plasma jet propulsion, instrumentation and calibration, and reentry studies for ablation and materials testing. The programs were designed to lead toward:

1. Electric propulsion (program transferred to Lewis Research Center in 1962).
2. Development of a device with high \dot{q} (Btu/ft.²-sec.) and precisely measured parameters to be used in nose cone materials testing (requirements essentially completed when the Army Ballistic Missile Agency group was transferred to NASA in 1960).

In addition to these major programs, assistance was provided to the Army Rocket and Guided Missile Agency work from 1959 through

1962, and a small materials testing facility was operated from 1958 to 1960 in the Propulsion and Vehicle Engineering Division (P&VE) of MSFC.

MSFC's function with respect to plasma-jet materials testing is unique among NASA's research centers. At the beginning of the development of materials suitable for an ICBM nose cone, a rather extensive materials test program by means of rocket engine exhaust had been underway at Redstone Arsenal long enough to obtain information establishing a limited number of materials as candidates for this end use. Additional materials test work was needed to supplement this program. Especially desirable were such factors as:

1. Very low contamination of the exhaust gas.
2. Duplication of the gas environment (air or synthetic air).
3. Higher enthalpy than could be obtained with other than exotic rocket fuels.
4. Longer times than the usual few seconds or minutes to provide information over an appreciable portion of the flight path.
5. Mach 2 to 5 to give hypersonic pressure and heat transfer distribution over the test model.
6. Tunnel size adequate to test full-scale critical areas of component parts.
7. Steady and continuously variable flow to simulate a portion of the trajectory.

Because rough data were already available on kerosene/peroxide engine exhaust testing programs, the desired information was detailed knowledge of the physical and chemical state of the gas as well as accurate understanding of the flow. The program of arc-jet materials testing was primarily an optimization of known materials and an understanding of the fundamentals of the ablation process. As the project progressed, a program of continuous and early publication was emphasized to enable other workers in the field to obtain such assistance as could be provided. Many installations were in the process of materials testing for rough separation of candidates in a variety of specific applications. The program here was that of testing a few selected samples in a well calibrated arc.

In the field of plasma physics and equipment development—more closely allied to pure research than many other phases of MSFC's plasma work—a wide range of problems has been attacked. Direct jet velocity measurements were made on the argon jet in the tunnel by means of the drum camera. The structure of variation of luminosity was shown to be electrical current fluctuation (Chapter 7, Reference 73). Data from 13 Langmuir probe runs have been presented (Chapter 7, Reference 15). This series of probe measurements was

taken in the argon plasma-jet tunnel in order to investigate the following problems associated with probe measurements:

1. Plasma potential and plasma-jet electrode polarity.
2. Probe heating effects.
3. Radial survey of the floating potential of the jet.
4. Effects of the probe holder.

The theory of the plane Langmuir probe has been developed to be appropriate to the experimental situations.

Temperature profiles for the nitrogen arc were calculated and illustrated (Chapter 7, Reference 29). Detailed information was given for argon at 2 atmospheres of pressure in an arc chamber. The absolute intensity profiles obtained were illustrated. A highly stable and uniform air jet was attained using a "long" front electrode at powers up to 120-kw. (Chapter 7, Reference 237). A tapered electrode gave nearly as satisfactory performance, but with a significant reduction in voltage, and increased mass flow range.

MSFC's work resulted in progress with the plasma head, nozzle, pressure measurement, velocity measurement, and trial run of spectroscopy techniques (Chapter 7, Reference 207). The program covered fabrication and calibration of the nozzle, tunnel modification, and a description of preparatory spectroscopic work which had been performed. During the course of the work to complete the hyperthermal wind tunnel, a multifaceted technical investigation was conducted with results including (Chapter 7, Reference 202):

1. Mach number determination in argon and ablation tests with graphite.
2. Considerable advancement in the operation of the air-plasma jet.
3. Development of the copper wedge, copper cone, and copper pitot probe for determining the free-stream Mach number of the air plasma jet.
4. Measurement of electron densities and electron temperatures in the plasma jet by means of Langmuir probes.
5. Conductivity measurements of fluid in the tunnel by a flux penetration method. The measured values were in agreement with theoretical predictions.
6. Tests with a new open jet diffuser, both hot and cold gas flow.
7. Gas dynamic flow measurements and calculations, electric plasma properties, and calorimetry.
8. Development of the one megawatt wind tunnel, pilot wind tunnel improvements, gas dynamic calculations, heat transfer calculations and measurements, electric plasma properties, and graphite probe measurements.

9. Increase in the power and pressure range of the head and auxiliary equipment.
10. Wind tunnel improvements, pilot wind tunnel calibration, gas dynamic measurements and calculations, heat transfer calculations and measurements, and imbedded electric probes.
11. Spectroscopic measurements and the difficulty due to the vibration of the test section. This work was part of the general program to measure temperatures of the various species and to determine the detailed kinetic state of the plasma as well as its composition.
12. Work with the tunnel. At a Mach number of the pilot tunnel, roughly M-2.5, a somewhat larger test jet would be available. The Mach 2.5 nozzle could reach the 150,000-foot altitude only at relatively high enthalpies. It appeared that some in-between value, possibly Mach 3.0, may be the best compromise choice for jet size and available range of densities and altitudes at any one enthalpy.

Instrumentation development on the program was extensive as evidenced by the appearance of items such as the total enthalpy and mass flow-density probe; the water-cooled copper hemisphere calorimeter; the transient calorimeter; and experiments on the static, pitot and Langmuir probes (Chapter 5). The overall approach was to attempt as many different techniques as seemed feasible, and to concentrate on the development of those which appeared most promising.

Reentry simulation and instrumentation studies have been fundamentally involved with attempts to reproduce the energies (enthalpies) which spacecraft will encounter during high-speed entry into the earth's atmosphere. Significant works are briefly covered here with proper notation being given (Chapter 7, Reference 237). The basic advantages of the arc-type facility for this work lie in:

1. The high obtainable fluid enthalpies.
2. The capability of using air, synthetic air, nitrogen or inert gases interchangeably.
3. The possibility of varying the gas temperature and pressure independently to produce a given heat flux with a range of gas enthalpies.
4. The ability to run continuously, and if necessary to program the power input and/or gas pressure during a run.

A basic weakness of these facilities lies in the relatively low Reynolds number which can be attained.

Enthalpies of 27,500 Btu/lb. were achieved in the arc generator at pressures of about 0.2 atmosphere. Pressure, heat transfer, Langmuir probe and spectroscopic measurements were calibrated.

Enthalpies in excess of 25,000 Btu/lb. were achieved near the end of the project period in a reliable 500-kw. vortex-stabilized arc generator using air or nitrogen as the working fluid. The electrodes were of water-cooled tungsten and copper.

Extremely steady, fully expanded jets (3-inch diameter, $M=3.0$) have been obtained by employing a water-cooled copper nozzle with large mixing chamber matched to a 500-kw. areahead. Heat transfer surveys using a $\frac{5}{8}$ -inch water-cooled calorimeter across the 3-inch jet showed a very uniform heat distribution, the \dot{q} profile being nearly flat with less than 10 percent decrease as long as the calorimeter remained inside the jet boundaries. Operation over a broad range of power while maintaining a consistently uniform jet has been achieved. For instance, the enthalpy could be increased from 2,000 to 15,000 Btu/lb. by increasing the current at constant mass flow (as in the simulation of a glide trajectory) without losing jet uniformity or stability.

Heat transfer data were obtained for the confined arc column. These provided some insight into arc-gas heating processes and laid the groundwork for the design of future, more advanced arc generators. Other arc chamber experiments furnished information on magnetic arc stretching and arc rotation.

Continuous tests of up to 1 hour duration have been successfully conducted with negligible electrode loss using nitrogen and with small (although continuous) erosion using air in the arc chamber. During the "nitrogen runs" varying percentages of oxygen were added in the mixing chamber. The jet was calibrated at enthalpies up to about 21,000 Btu/lb. Total enthalpy profiles showing excellent uniformity (only about 4 percent variation) at the high enthalpies were obtained with a newly developed probe. They verified the parabolic entry environment.

The variation of the stagnation-point heat transfer with enthalpy and pressure was found to agree very well with that predicted by Lees' theory over a wide range of enthalpies (5,000–21,000 Btu/lb.) and pitot pressures (0.01–0.2 atm). In absolute value the heat transfer also agreed quite well with Lees' theory using the Sutherland viscosity formula. This result is tentative because of various uncertainties in both the measurement (radiation) and the theoretical values (viscosity).

The measured pressure ratios (pitot-to-total vs. static-to-total) varied with increasing enthalpy in a manner suggesting near equilibrium rather than frozen flow expansion in the nozzle. This result is also tentative.

Several other jet-calibration and measuring techniques were further developed in the work. The direct velocity measurement using micro size tracer particles was prepared for detailed surveys across the jet.

The mass flow density (Pu) probe was also made ready for use. The Langmuir probes and the spectroscopic techniques were advanced in varying degrees, but require considerable further work for reliable interpretation of the measurements to determine electron temperature, density, and atomic (translational) temperature.

Other items include:

1. A most satisfactory design (17,202) of a calorimeter probe was tested and demonstrated to have a large reserve of cooling capacity in the hottest areas of the jet.
2. In graphite ablating experiments (10), graphite rods appeared to provide a convenient means for measuring the relative heat flux distribution across the tunnel jet since equilibrium temperatures and ablation rates can be easily measured.
3. Extensive ablation tests were performed with Micarta 259-2 (4, 5) in air, argon, and nitrogen at elevated power and pressure levels.
4. A most important advancement was made in nozzle design: a spiral cooling water chamber was incorporated as were radiation-cooled nozzles for the small thrusters.

High intensity plasma jets have demonstrated potential application not only in the ablation studies of protective materials on space vehicles reentering the earth's atmosphere and in the propulsion of such vehicles, but also in the studies of the refractoriness of materials for nonspace use (4), and in the adaption of the small thruster units to high intensity light sources.

The development of the hyperthermal tunnel began in 1957 after considerable materials testing experimental work with smaller pilot tunnels using argon and air. In 1958 the completion of a small pilot tunnel and study of argon, with input power in the range of 20-100 kw., marked the start of work toward a proposed one-megawatt hyperthermal facility. Argon was chosen as the working fluid because only low voltage equipment was available, and the development of water-cooled electrodes and calibration instruments was less difficult in an oxygen-free environment. Once successful operation was attained with argon, similar studies were carried out in the pilot tunnel using air. With the knowledge and experience gained in the pilot tunnel, the one-megawatt tunnel was first run on October 15, 1959. A portion of the calibration and development testing was completed in the following year. Of particular interest were the extremely well-filtered power supply and the "Fasteax" pictures taken to show the effects of filtering on the exhaust plume. Motion pictures of the plasma plume show that density variations disappear

and the stability of the arc increases as the degree of filtering is increased.

In March of 1960, a well-defined one-megawatt hyperthermal tunnel was put into active operation. Some of the advanced features of this tunnel include:

1. Wide range of operating conditions: Pressure ranges between 0.1 and 10 atmospheres and enthalpy ranges between 2,000 and 25,000 Btu/lb. were obtained.
2. Continuous runs up to 1 hour.
3. Low contamination rate: In conjunction with the long run times, contamination rates far less than 0.1 percent have been achieved at the lower power and pressure levels (500-kw.). At the higher power (1 megawatt) contamination approached 1-2 percent.
4. Uniform and steady flow: With the use of suitably screened mixing chamber, and by properly balancing the nozzle exhaust and vacuum tank pressures, extremely steady and uniform flows have been achieved (no fluctuation visible to the eye) and axial and radial variation of the heat transfer rate over the test region was less than 10 percent.
5. Large jet size: The standard nozzle size was chosen as 3 inches in diameter. Larger nozzles up to 6 inches in diameter could be accommodated at certain high-enthalpy, low-pressure test conditions, but these were not built.
6. Continuously variable test environment: The enthalpy and pressure could be varied continuously throughout a run to simulate the time history of portions of reentry flight trajectories by varying the power input to the generator and the mass flow rate.
7. Radial and axial calibration measurements: Accurate calibration instruments were developed to provide local ("space-resolved") measurements of pitot pressure, static pressure, heat transfer rate, local total enthalpy, mass flow density and velocity.
8. Determination of gas state: In addition to the quantities mentioned in Item 7 above, other flow quantities were investigated including flow density, electron temperature and density, and spectroscopic temperature and species determination. Various types of analysis procedures were worked out in order to provide information regarding the gas state.

(Work concerning the Plasma Jet Propulsion Program undertaken by MSFC was discussed in Chapter 2.)

NASA Developed Instrumentation for Measurements in Partly Ionized Gases¹

INTRODUCTION

The information in this chapter is a result of development work on instrumentation used in experimental work with hot gases and plasmas in the following laboratories:

NASA Ames Research Center, Moffett Field, California,
 NASA Langley Research Center, Hampton, Virginia,
 NASA Lewis Research Center, Cleveland, Ohio,
 NASA Marshall Space Flight Center (MSFC), Huntsville, Alabama,
 The Plasmadyne Corporation, Santa Ana, California, under contract with NASA.

The following sections concern the instruments and the methods for their use in making observations and measurements of electrically heated gases and plasmas of low degree of ionization.

Parallel to the work with plasma jets and plasma, tunnel materials of new composition and structure were developed and extensively tested in various gases, at high enthalpy levels, and at supersonic speeds. Special instrumentation has been used for this material testing as well as for studies of the interaction of plasma streams with electrical and magnetic fields, with different materials, and with radiation. In addition to work in the laboratories, special instrumentation is being carried on satellites and deep space probes for control, measurements, and observation. The instruments and methods discussed in this summary are not unique; their principles come from many other fields. The instrumentation is strongly characterized by the objective of the measurement of such conventional parameters as pressure, temperature, and density under prevailing conditions, e.g., in an electric arc or in a subsonic or supersonic flow of electrically heated gas.

¹ Much of the material in this chapter was prepared by Mr. Woldemar F. van Jaskowsky, Forrestal Center, Princeton University, Princeton, New Jersey.

Under the conditions of a gas in the plasma state, many of the measured quantities are undergoing fluctuations which may be too rapid for detection and measurement by steady state conventional instrumentation. Thus, instrumentation with a high time resolution was developed for this purpose. The interpretation of a measurement in a plasma is complicated by the possible simultaneous existence of a number of different constituents at widely different temperatures. Evidently, many more detailed measurements are needed for a meaningful characterization of the same gas, say, at room temperature.

In this review the emphasis will be placed on instrumentation which is characteristic for arc heated plasmas and jets; hence, a number of instruments will be omitted from the detailed description to follow. In this chapter, the following types of detectors and indicating and recording instruments are regarded as standard commercially available apparatus:

- Pressure gauges and pressure transducers;
- flow rate meters, rotameters for gases and liquids;
- thermocouples and thermopiles for temperature and temperature difference measurements;
- voltmeters, current-meters, wattmeters;
- recording instruments and oscillographs, oscilloscopes.

For completeness, some instruments and methods of measurement will be mentioned briefly even though they may not fit the classification for this review. These are instruments which have been used successfully in other fields and have potential for future application. The following sections have been arranged according to the characteristics of the instrument or its principle, rather than by the significance of the particular instrument for the development, calibration, study, or control of plasma jets, tunnels, and other devices. This arrangement allows the instrument classification to be isolated from the theories of the interaction of the flow with materials and fields. Such theories and their experimental verifications have been the subject of extensive work discussed in another portion of this document and elsewhere in the literature.

PRESSURE MEASUREMENT INSTRUMENTATION

In studying the plasma stream, a knowledge of the static pressure and the impact pressure, as well as a knowledge of the total pressure measured in the plenum chamber of the tunnel is of interest.

While we will not discuss the interpretation of every pressure measurement under special conditions, it is of interest to report on some special designs of pressure probes that can withstand the plasma environment for continuous monitoring, or for times of sufficient length

to carry out radial and axial surveys of streams of plasma. Measurements with a high time resolution have gained significance in the detection of fluctuations (e.g., in alternating current plasma generators). A few representative instruments are discussed in the ensuing paragraphs.

The use of a typical impact pressure probe of 0.3 in. outside diameter, with 0.2 liters/sec. flow of cooling water at 4 atm. has been reported by the Lewis Center for a nitrogen arc jet with up to 3 atm. impact pressure at enthalpies up to approximately 17,000 Btu/lb. The probe had an inside diameter of $\frac{64}{1000}$ in., and was connected to an aneroid gauge.

A probe has been used by the Lewis Center for surveys of both static and impact pressures across the diameter in a plenum chamber. The 0.1 in. diameter tap in the boron nitride tip of a $\frac{1}{4}$ -in. diameter stainless steel tube faced the gas stream for impact pressure surveys, and was turned by 90° for static pressure measurements.

A combination probe was designed at the Lewis Center for simultaneous static and impact pressure detection (Figure 5.1). The impact probe of 0.19 in. O.D. and 0.12 in. I.D. with a 10° inside chamber protruded from the 0.37 in. O.D. tube with three 0.12 in. diameter holes 120° apart, for static pressures.

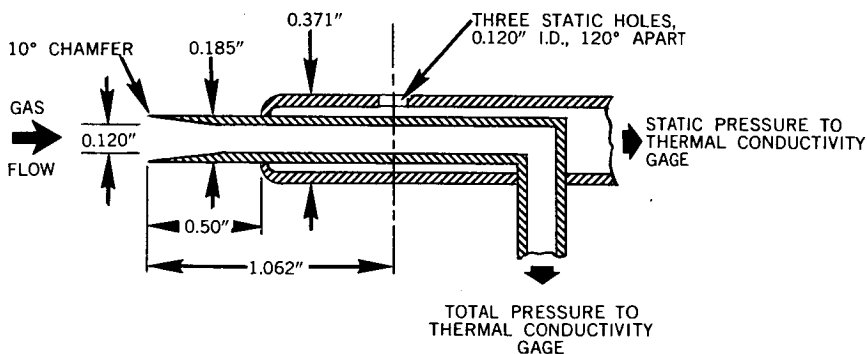


FIGURE 5.1.—Probe for measuring pitot- and static-pressure.

Courtesy of Lewis Research Center

For time-resolved pressure measurements from 200 microns to 200 mm., strain gauge transducers can be used. For pressures from 1 mm. down to a few microns, a small ($\frac{3}{4}$ in. by $\frac{5}{8}$ in.) vibrating diaphragm transducer has been developed at the Ames Center (Figure 5.2). The diaphragm is a few thousandths of an inch from both, and is parallel to a driver and a detector electrode. An electrical signal is applied between the driver electrode and the vibrating diaphragm which

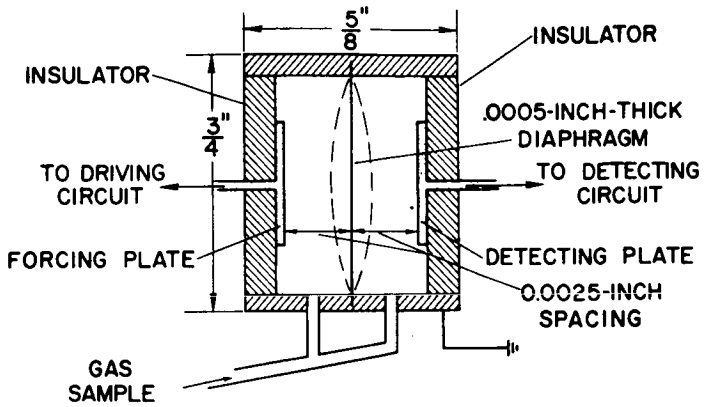


FIGURE 5.2.—Vibrating diaphragm pressure transducer.

Courtesy of Ames Research Center

delivers work to the gas. The electrical power which is required to keep the diaphragm vibrating at a fixed amplitude is, then, a measure of the expended work as a function of the pressure of the gas.

A time-resolved pressure measurement technique for air at pressures from 200 microns to 800 microns has been investigated in the laboratory at MSFC. The number of electrical breakdowns per cycle of an applied sinusoidal ac voltage in an air gap between insulated electrodes was counted on an oscilloscope screen display. The calibration of the gap was accomplished with an Alphasatron.

CALORIMETERS

HEAT TRANSFER MEASUREMENTS

In addition to other measurements, the rate of heat transfer from a plasma jet to the surface of a body is an important characteristic of the flow. The design and uses of a number of different types of calorimeters have been reported. Most measurements of heat transfer rates have been made with water-cooled instruments that could be subjected to the environment of a plasma for a considerable length of time.

CONTINUOUS OPERATION CALORIMETERS

Water-cooled calorimeters of various designs have been used to measure typical heat transfer rates from 0.1 to just below 2 kw./cm.² in argon, helium, nitrogen, carbon dioxide, and air. The heat transfer rate to a copper hemisphere of typically 5/8-in. diameter is computed from the rise in temperature of the cooling water and its flow rate through the instrument. The temperature rise of the cooling water is measured by immersed thermocouples. The thermocouples and

their associated circuitry require effective electrical insulation from the cooling system and the remainder of the apparatus if the water exhibits a high electrical conductivity.

The Plasmadyne Corporation (References 204 and 208 in Chapter 7) has designed a calorimeter that makes use of two separate paths for cooling water to prevent heat flow from other parts which, in turn, contributes to the rise of the temperature of the cooling water. The design of the copper hemisphere calorimeter with two water cooling systems is shown in Figure 5.3. A steady reading in a steady plasma stream can be achieved for this instrument in 17 minutes. Normally, a third of a gallon of cooling water (at less than 15 atm.) may flow through the calorimeter in one minute. It is claimed that this instrument can reproduce data with an approximate accuracy of 5 percent.

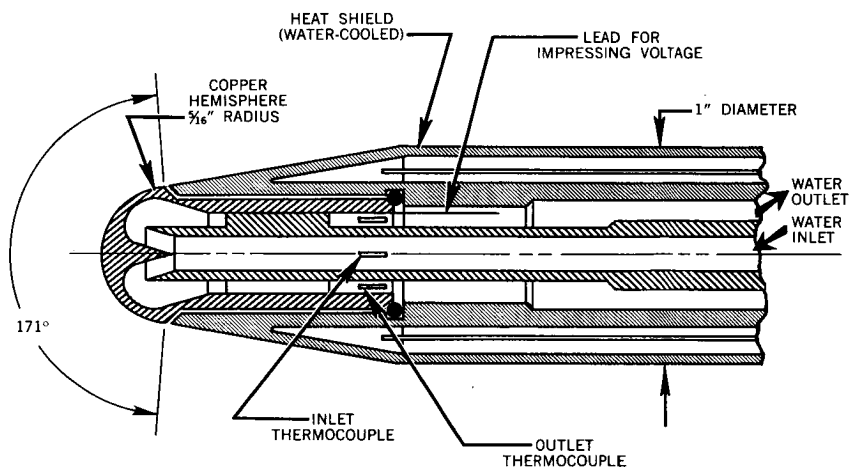


FIGURE 5.3.—Copper water-cooled calorimeter.

Courtesy of Plasmadyne Corporation

At a MSFC Laboratory, the influx of heat from other sections of the calorimeter was controlled by the use of monel tubing of small thermal conductivity and a graphite sleeve around the outer tube of a water-cooled copper hemisphere calorimeter. With a calorimeter of this design, heat transfer rates were compared for streams of plasma with equal power in the gas and equal mass flow rates, but with different nozzle throat diameters, and it was found that the heat transfer in a stream from a 12.7-mm. diameter throat was several times larger than that in a stream from a 9.5-mm. throat diameter.

The hemispherical calorimeters measure the transfer of heat to a cold copper surface, and they yield values of heat flux which are integrated over the hemisphere and which include the stagnation region. The theory may then be invoked to obtain stagnation point heat transfer data from the integrated measurements.

The continuous operation-type calorimeters may be calibrated by comparing the total measured heat flux with the power in the gas which is known from the electrical and gas input data.

An instrument at MSFC for the measurement of stagnation point heat transfer detects the heat flux to a flat 1-cm.² circular area which is thermally insulated from a flat surrounding shield by its own separate water cooling. The shield as well as the sensing part are made of copper and are electrically insulated to prevent their acting as electrodes for the arc plasma. In a laboratory at the Ames Center, the heat flux in a plasma stream was measured with two water-cooled 1/4-in. diameter copper tubes arranged symmetrically and transverse in the stream.

In another calorimeter design at the Lewis Center, the temperature gradient along a cylindrical 0.3-in. diameter constantan body was measured with two thermocouples. The blunt front of the cylinder was exposed to the flow, while the sides were protected by a shield. The rear end of the central metal cylinder and the 1/2-in. diameter constantan shield were water-cooled. Consistent heat flux measurements were reported for different shapes of the detecting metal plug. The same principle of measuring the temperature gradient along a thermal conductor is used in a 3/8-in. diameter calorimeter with a flat copper nickel disk as its face. The periphery of the disk is connected to a water-cooled copper tube. The hot junction thermocouple is formed by the junction of a copper wire with the center of the rear side of the disk. This calorimeter was used to measure heat fluxes up to 0.4 kw./cm.², and for monitoring the heat transfer in a megawatt input plasma jet simultaneously with and separate from radiative heat transfer measurements.

The catalytic effectiveness of different surfaces has been compared during the work with calorimeters at the Ames Center. Polished copper was found to be the most active surface, while the least active surface was provided by a coating of 5,000° thickness of silicon monoxide on copper.

TRANSIENT MEASUREMENTS

One transient measurement-type calorimeter at the Ames Center used a small slug of metal (copper, aluminum) which was supported and thermally insulated at the sides by a refractory material. The

rate of rise of the temperature of the slug of metal then is a function of the rate of heat transfer.

A small slug of metal may also be used as a "time to melt" transient-type instrument. The metal slug is exposed to the heat flux from the flow and the time is measured until it melts.

It is difficult to calibrate such "transient" instruments for larger heat transfer rates, because both the heat conductivity and the specific heat of the material change considerably with temperature. It appears that transient heat transfer measurements thus far have been found to be less accurate than the water-cooled continuous operation type calorimeters.

A calorimeter in a plasma stream, as well as any other type of probe, will collect ion and electron currents and, therefore, acquire an electrical potential. In the Plasmadyne laboratory, a study was made of the effects of electrical currents on the heat flux measured by the calorimeter. Voltages up to ± 50 volts were applied, with currents of a few amperes flowing to the calorimeter which then measured heat fluxes and showed an increase of up to more than 10 percent.

TOTAL ENTHALPY—MASS FLOW PROBE

For local measurements of total enthalpy and mass flow in a plasma stream a probe has been developed at the Plasmadyne Corporation which swallows all of the flow impinging on the sharp-edged orifice. Passing through the water-cooled inside, the gas is cooled and its temperature, pressure, and flow rate are recorded before it is exhausted through a valve to a pump. A shield with separate water-cooling prevents heat influx from the sides of the probe.

The probe was calibrated by comparing the measured total enthalpy in the stream with the value which was computed from the known electrical and gas flow data.

THRUST MEASUREMENT

The measurement of the thrust (to a fraction of a pound) of a small arc plasma jet at the Plasmadyne Corporation (References 201, 203, and 207 in Chapter 7) was carried out with the jet mounted on a thin cantilever which was backed by a strain gauge type "load cell," consisting of the balanced bridge of unbonded resistance wire.

In thrust measurements of electrical devices forces of electrical and magnetic origin arise and must be accounted for.

PHOTOGRAPHY

No difficulty is encountered in photographing highly luminous plasma flows. An interesting example is the photograph of a plasma jet in argon shown in Figure 5.4. The jet was photographed by a

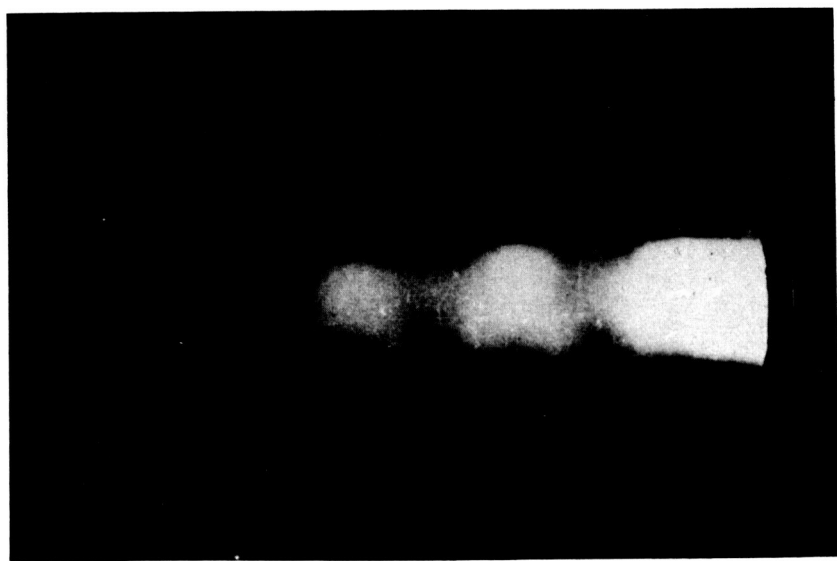
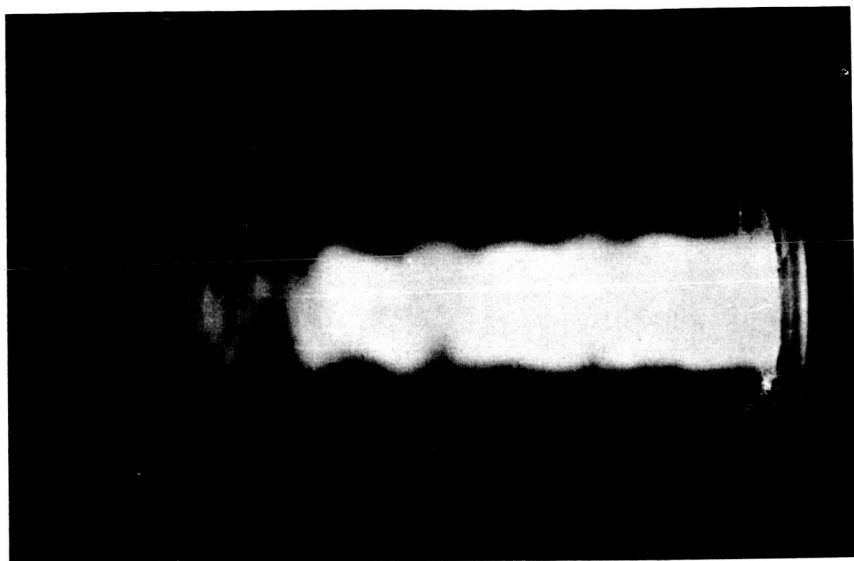


FIGURE 5.4.—Plasma jet in argon.
Courtesy of Plasmadyne Corporation

camera with a focal plane shutter set for 0.001 sec. exposure. The shutter slit motion was parallel to the axis of the jet; thus a few inches of jet length were compressed into one picture. The jet shows the 180-cycle ripple of the rectifier-type power supply, and the cork screw motion of the vortically stabilized argon jet.

In a plasma stream, regions which differ in temperature and composition emit radiation of different color characteristics. For example, a photograph (of an argon $M=3$ jet) taken in ultraviolet light at the Plasmadyne Corporation (References 200 and 202 in Chapter 7) showed only the outline of the outer edge of the flow—and also only the upstream edge of the shock on a wedge—in contrast to the usually visible bright luminescence of the entire flow cross-section.

For flow visualization at low densities a glow discharge system was designed and successfully used at the Ames Laboratory. The model in the test section was at ground potential, and was connected to the negative terminal of a maximum 10 kv., 250 ma. power supply. The high potential was connected to two anodes which were mounted flush with the test section walls opposite the model. The tunnel walls were insulated by a layer of aluminum oxide. Regions of different density show different radiance in the glow discharge. Shockwave photographs were obtained in air at $M=15$, $P_T=1,000$ psi, $h_T=9,000$ Btu/lb.

FRAMING CAMERAS

In a Langley Research Center laboratory, a Fastax framing camera was used (at typically several thousand frames per second) to observe the arc inside a coaxial plasma accelerator with an axial magnetic field. Argon and helium flows at 0.2 to 5.0 grams/sec.; pressures of 1 to 50 mm.; currents of 50 to 250 a.; voltages from 35 to 140 volts; and axial magnetic fields from 1200 to 3000 gauss were used. From the failure to observe arc spokes, the conclusion was drawn that the discharge between the coaxial electrodes was of the form of an arc disk. In this particular case, a supplementary Kerr cell picture was taken with very short exposure time, and it confirmed the absence of arc spokes.

Movies at a rate of 24 frames per second were taken in a small hypersonic arc tunnel at the Langley Center to follow the establishment of the 3-in. diameter flow over $\frac{5}{16}$ in. and $\frac{1}{2}$ -in. diameter pitot probes, after arc ignition.

At the Lewis Center, a high-speed framing camera was used to reveal the nature of an arc discharge. In a concentric dc arc heater (100 to 200 kw.) with an axial magnetic field of 1200 gauss, high-speed motion pictures at 4,000 frames per second and an exposure time of 4 μ sec. per frame revealed the diffuse nature of the arc. It was so diffuse

that a rotational speed could not be deduced. With a reduced field and a reversed direction of the vortical flow of argon or nitrogen, a distinct arc was observed.

Cameras with exposure rates of several thousand frames per second have been used quite successfully to observe the electrical discharges in arc chambers and rotating arcs in magnetic fields. The luminosity and flow fluctuations have been observed in transparent quartz plenum chambers and nozzles, and on wedges and blunt bodies in a plasma flow.

Very short exposure times of the order of 10^{-8} seconds and shorter were achieved with Kerr cell shutters at the Langley Center for the observation of very fast phenomena. The Kerr cell requires a voltage pulse of a few tens of kv. which is applied to the two plates in the cell at the time of exposure.

INSTRUMENTS FOR VELOCITY DETERMINATION

The progress of inherent luminosity fluctuations in a gas or a plasma stream has been recorded on film in a rotating drum camera at the Plasmadyne laboratory. While the luminous regions travel down the plasma jet, their images on the film are drawn out to streaks the slope of which, together with camera magnification and speed of film travel, allows the computation of the velocity of the luminous regions in the jet. This velocity may be identified as the stream velocity under the assumption that the luminosity fluctuations travel in phase with the stream.

Some typical measurements in a $M=3$ argon tunnel at 60 kw. input yielded velocities from 9,200 to 9,800 ft./sec., while the calculated velocity at these conditions was 8,700 ft./sec.

For a vortex-stabilized arc plasma jet which was heated from a rectifier power supply, the luminosity fluctuations have been analyzed to travel at two distinct velocities: (1) the velocity of the stream, and (2) the stream velocity plus the local speed of sound.

In another experiment at the Plasmadyne laboratory, boron nitride particles of less than 5μ diameter were introduced into the flow, and their progress in the stream was recorded with a drum camera at a small depth of focus with external illumination of the particles. In this work with tracers in a vortex stabilized plasma jet, it was shown that the axial velocity can be expected. It was observed to have a minimum in the center of the jet and a maximum at a radius intermediate between the axis and the outside of the jet.

The luminosity fluctuations in a plasma stream may be observed with two photomultiplier tubes whose signals are recorded on a double-beam oscilloscope. The photomultiplier tubes are focused, or col-

limited, for two axial stations—usually a distance of approximately 1 in. apart—along one stream line. Also with this method a spread of the velocities of travel of the luminosity fluctuations was observed.

Faraday's law has been applied to measure plasma stream velocities of nitrogen in a 4-in. diameter tunnel at $M=6$, 12,000 Btu/lb., and 5×10^{-3} lb./sec. An electromagnet supplied a magnetic field perpendicular to the stream direction. The electrical field was determined from a measurement of the potential between two $\frac{1}{8}$ -in. diameter cylindrical electrodes which were inserted into opposite edges of the flow, perpendicular to both the stream direction and the magnetic field. The velocity determinations in a plasma stream by this method checked well with velocity measurements by other methods.

SPECTROSCOPY

In spectroscopy the frequency range from x-rays to μ waves is available for diagnostic instrumentation for plasmas. However, only the visible and the near ultraviolet range of radiation has been of interest in the present work.

Spectroscopic instrumentation disperses incident radiation as to its wavelength, and detects the intensity photographically or photoelectrically. The record needs to be calibrated with respect to both wavelength and intensity with suitable light sources. The photodensitometric reduction of a spectrogram is a tedious task.

The intensity versus wavelength record may contain line and continuum radiation in both emission and absorption and may be interpreted for (1) the identification of the emitting or absorbing material, (2) the distribution of the material in the region under survey, and (3) the state of the material, such as the temperature.

The spectrographs of various types and design, as well as photographic and photoelectric equipment with power supplies and oscilloscopes, are now standard apparatus.

According to the manner in which spectrographic instrumentation is used, and depending on the interpretation of the record, there may be a justification in identifying some of the spectroscopic methods as instrumentation for "species identification," "thermometry," and "density measurements."

IDENTIFICATION OF SPECIES

The simultaneous appearance in a spectrum of a number of emission or absorption lines of molecular, atomic, or ionic origin will identify that particular species as present somewhere in the path of the light. It is, however, a matter of further analysis to determine more precisely the distribution of the identified material along the path of light.

TEMPERATURE

In an MSFC laboratory, an excitation temperature was derived for an argon plasma from a measurement of the relative intensities of the 3,903 Å. and 4,005 Å. emission lines of iron which was present as an impurity. Since for these lines the transition probabilities are known from other measurements only the following assumptions remain: (1) that the emitted light could escape through an "optically thin" medium, i.e., without absorption, and (2) that the temperature was referred to a sufficiently small volume within which it did not vary.

The "ablation temperature" of a $\frac{3}{4}$ -in. diameter graphite hemisphere was determined spectroscopically at MSFC in a plasma stream of a velocity just below Mach number 1, with a heat flux of .5 kw./cm.² to a cold probe at the model position. Spectra which were emitted by the ablating model in the wavelength range from 6,500 Å. to 9,500 Å. were photographed on I-N plates together with the spectrum of a standard tungsten band lamp located at the model position. An emissivity of 0.85 was assumed for the graphite samples. For the measurements, the 8,000 Å. region was found to be free of lines and bands and therefore was used. The standard lamp calibration at 6,650 Å. with an optical pyrometer could be used with known tungsten data to obtain the calibration at 8,000 Å.

In a Langley laboratory the relative intensities of spectral lines were measured to derive temperatures in plasma jets of 0.7 to 2.5 megawatts, and tunnels of 1.5 to 10 megawatts input. For the heater section with copper electrodes, the intensity ratio of the 5,153 Å. and 5,700 Å. copper lines yielded an excitation temperature. A "rotational" temperature was derived from the intensity distribution in the CN spectrum (4,197 Å. to 4,216 Å.) when carbon electrodes were used.

Once the temperature is known for a small volume of the plasma, the temperature determination can be extended to other parts of the plasma by comparing the emission coefficient of the volume of known temperature with that of the volume whose temperature is to be determined.

The simultaneous existence of a set of different temperatures was demonstrated at the Ames Center in the plenum chamber of a wind tunnel. Nitrogen at 0.005 lb./sec. was heated in an arc chamber at approximately $\frac{1}{3}$ atm. and up to 12,000 Btu/lb. (to produce a Mach number of 5.6 in a 4-in. diameter stream). The nitrogen in the plenum chamber showed a vibrational temperature of 7,000° to 9,000° K., a rotational temperature of 2,000° to 3,000° K., and a degree of ionization corresponding to 4,500° to 5,000° K.

An absolute spectroscopic temperature determination is possible in a gas or plasma at a given pressure if it is further known that the

temperature somewhere in the gas exceeds the particular temperature in another region of the plasma where the emission coefficient has a maximum. This method was originally introduced in astronomy and then adapted to high temperature arc work. It is sometimes referred to as the ionization temperature. The intensity maximum is easily identified on a stigmatic spectrogram, while the temperature at the intensity maximum can be calculated by invoking the perfect gas law, the Boltzmann relation, and the Saha equation, and further assuming that the emitted light is not attenuated along its path.

The Ames laboratory reported $15,500^{\circ} \pm 750^{\circ}$ in a 1-atm. 8 g./sec. argon jet (typically at 26 kw. input). The temperature was derived from the maximum intensity of the 3,949 Å. argon line. The laboratory has prepared graphs of the maximum temperature dependence on pressure for pressures from 0.001 to 1.0 atmosphere for one argon line, three hydrogen lines, and one helium line.

Some earlier work made use of the low ionization potential of sodium by adding sodium chloride to an argon jet and determining the $4,700^{\circ}$ K. "ionization temperature" isotherm on a photograph which was taken through an interference filter for the D-lines. Previously an excitation temperature of $8,000^{\circ}$ K. which was obtained from the intensity of two iron impurity lines had been reported for the same plasma jet. However, the different temperatures may very well refer to different radial locations in the plasma jet near the nozzle exit.

Instead of photographically recording a stigmatic spectrogram, the intensity across the arc was recorded photoelectrically in the Plasma-dyne laboratory by sweeping an image of the arc across the spectrograph slit with a rotating mirror and detecting the intensity with one or several photomultipliers at the exit of the spectrograph. The arc jet was operated with nitrogen and argon at slightly-above-standard pressure in the arc chamber, and at approximately $\frac{1}{5}$ atm. in the jet chamber. Maximum intensity temperatures were computed and observed for bandheads in the nitrogen arc; temperature profiles were then obtained by the mentioned method.

DENSITY

The ion density in a dense plasma was estimated from the principal quantum number of the last observable line in the Balmer series of deuterium. The method is based on a theory which was originally derived by Inglis and Teller. More recently the theory has been extended to compute the lowering of the ionization potential at high densities.

SCHLIEREN AND INTERFEROMETER INSTRUMENTS

Flow field photographs were made at the Ames Center, in a $M=10$ to 20 tunnel for air heated by an arc in the mw. range with a vacuum schlieren system. Most of the optical components were accommodated inside a tube which was evacuated to 100μ . The light beam makes a double pass through the test section to and from a 15-ft. focal length spherical mirror. This system is reportedly still useful at low densities where the sensitivity of conventional schlieren and shadowgraph methods is no longer sufficient.

Density determinations with elaborate interferometers have been reported in plasma physics. Interferograms of plasma jets have been obtained by using a light source of high intensity. The interpretation of the fringe shifts for cylindrical plasma jets with strongly varying molecular, atomic, ionic, and electron concentrations, and their resonances is a difficult task.

EXTERNAL MEASUREMENTS

VOLTAGE, CURRENT, AND POWER

Electrical instruments for measurements external to plasma jets include meters for electrical potential current, power, and phase, as well as oscillographs and oscilloscopes for the observation and recording of fluctuations. These instruments and the methods for their use are entirely standard, and are mentioned for the sake of completeness.

MICROWAVES

The use of microwave instrumentation (for the determination of the electron density and temperature in a 3-in. diameter cyanogen-oxygen flame at atmospheric pressure) has been reported by the Langley Center. The 62.5-Gc. apparatus is standard equipment and was used with a crystal detector to measure the attenuation of the microwaves in transmission. For this experiment, the wavelength and horn dimensions were approximately $\frac{1}{10}$ of the flame diameter. Cylindrical symmetry of the distribution of the density and temperature in the flame were assumed. The transverse attenuation was reduced to the radial electron density profile using a calculated collision frequency. From the electron density, the temperature distribution was computed by using the Saha equation, the known pressure, and ionization potential. Electron densities around $10^{12}/\text{cm}^3$ and temperatures around $4,300^\circ \text{K}$. were obtained.

Microwave reflection, attenuation, and phase shift form a complete instrument for electron density determination which is used extensively in shock tube work and in plasma physics.

LANGMUIR PROBES

Single probe measurements have been carried out at the Langley Center in a coaxial device at 30 to 300 μ pressure of nitrogen or argon seeded with lithium which was evaporated from the inside of the hollow center electrode. The device had a 3-in. diameter with a short accelerating section, just outside of which typical electron densities of 10^{11} to 10^{12} per cm^3 and electron temperatures of 10^5 to 10^6 $^\circ\text{K}$. were derived from a complete probe characteristic which covered 200 volts and up to 10 ma. of current. Some of the probe results compared well with 3-cm. microwave measurements.

Two Langmuir type probes were used in a 4-in. diameter, $M=6$, 2,000 Btu/lb. at 0.005 lb./sec. nitrogen jet in a tunnel at the Ames Center to determine the velocity of the stream. The probes were copper wires insulated everywhere but at their ends. They were 1 inch apart in the flow direction and far enough apart transversally to prevent mutual shock wave interference. From the time between identical signals from the two probes on the recorded oscillogram and the spacing of the probes, velocities from 5,000 to 30,000 ft./sec. were obtained. The most probable velocity was read from a plot of the experimental data as a probability distribution. The assumption here is that the electrical disturbances travel with the speed of the gas.

In a MSFC laboratory, a simplified double probe theory has been developed for weak Coulomb interaction for conditions of temperature and density such that the Debye length is small relative to the size and separation of the probes. These conditions define a range of temperature from $5,000^\circ$ to $8,000^\circ$ K. and pressure from 1 to 10 cm. of Hg for an argon plasma. Unlike other theories, this theory does not admit positive probe potentials relative to the plasma.

Measurements with a double probe of short 0.1-cm. diameter wires, 0.7 cm. apart, in an argon jet of typically 25 kw. input at 1 cm. pressure yielded electron temperatures just above $30,000^\circ$ K. Saha equation temperatures were computed from the ion current and the known pressure and were found to be just below $8,000^\circ$ K.

A $1/4$ -in. diameter graphite rod has been used as a single Langmuir probe at a Plasmadyne laboratory (References 200, 202, and 203 in Chapter 7) for the study of a $M=3$, arc-heated, 20- to 40-kw. argon jet of 1 in. diameter. Typical probe voltages of up to 30 volts produced several amperes of probe current. The measurements yielded electron temperatures from $10,000^\circ$ to $50,000^\circ$ K. and electron densities of several 10^{12} per cm^3 .

The probe was allowed to heat up during the measurements. Both the positive and negative branches of the probe current were increased,

except in a small region on the negative side of the floating potential, when the probe was allowed to heat to incandescence.

The probe potentials were referred to the metallic nozzle, and both the floating potential and plasma potential were found to go strongly positive when the center arc electrode was positive and the negative arc electrode was connected to the nozzle. A survey of the floating potential along a diameter through the test chamber showed the potential to increase by $1\frac{1}{2}$ volts outside of the plasma jet relative to the floating potential inside the jet. The floating potential remained practically constant along the remainder of the 12-in. radius of the test chamber up to the immediate proximity of the wall. To establish essentially uniform flow properties over the entire probe surface, the fringing effects at the edges of the probe surface must be negligible. For this reason, the plane cylindrical probe was enclosed by a concentric guard ring as shown in Figure 5.5. The guard ring was held at the probe potential everywhere along the characteristic. Differences in potential of only a few millivolts between the probe and the guard ring produced significant changes in probe current; letting the guard ring float yielded drastically different characteristics and somewhat different results of the reduction.

Also shown in Figure 5.5 is a "flat plate probe" with a concentric probe guard ring assembly mounted flush with the upper plate surface, which was mounted parallel to the flow and was covered by the viscous boundary layer on the plate. The derived electron temperatures and densities differ relatively little from those obtained with the cylindrical probes.

The theory for the single Langmuir probe has been extended to plasmas which have a drift velocity relative to the probe. Elsewhere, this work has been used to estimate plasma flow velocities.

In an application of probe theory, a variable electrical potential was impressed on the copper hemisphere of the water-cooled calorimeter described in the section on "Continuous Operation Calorimeters," relative to the nozzle of the tunnel, and the heat transfer was measured as a function of voltage and current. The heat transfer had a minimum at slightly negative voltages, and rose by typically 10 to 15 percent for both positive and negative potential. For a given potential, the current and the heat transfer decreased with increasing distance from the nozzle. Typical voltages were up to 50 volts; currents were from a few to several amperes.

After the insertion of the calorimeter into the flow, the heat transfer showed a hysteresis for increasing and decreasing voltages for a period of approximately 10 minutes, after which time hysteresis effects were no longer observed.

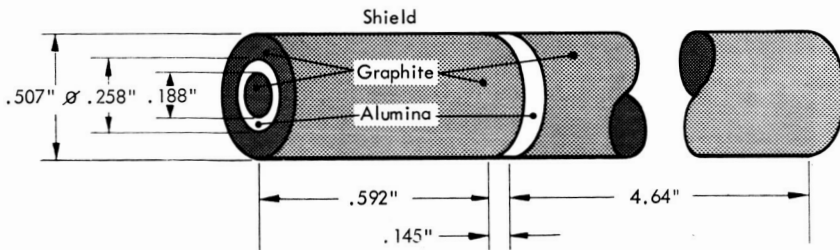
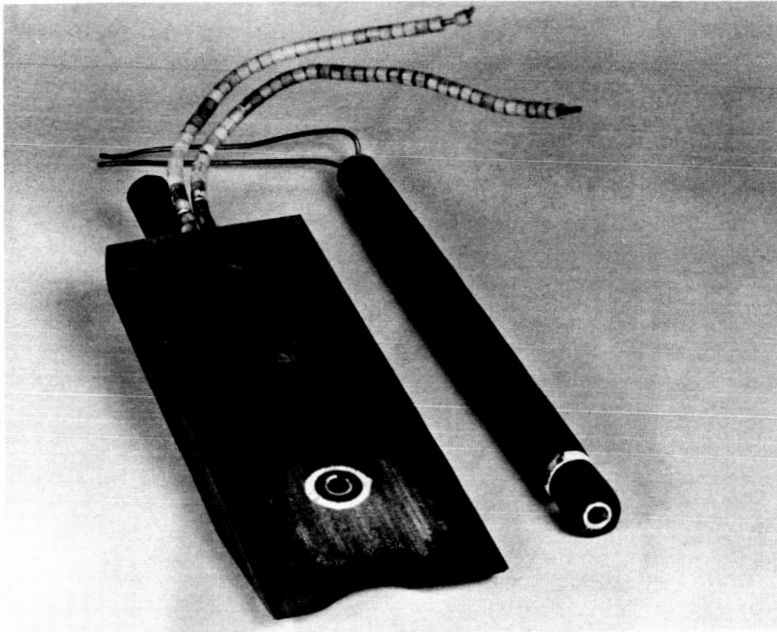


FIGURE 5.5.—Flat plate and stagnation point Langmuir probes.

Courtesy of Plasmadyne Corporation

MAGNETIC FIELDS

Magnetic field measurements in a plasma with very small coils is commonplace in plasma physics. In the coil a voltage is induced which is proportional to the change of the magnetic flux through the coil. With a R-C-integrating circuit a signal is produced which is proportional to the magnetic field.

CONDUCTIVITY MEASUREMENT

One type of conductivity measurement is based on the change of the inductance of a coil, when a plasma is present inside the coil. The coil is part of an LC circuit, the resonant frequency of which is detected. When the plasma is present inside the coil, the current in the plasma is limited to a skin on the outside of the plasma. The thickness of the skin depends on the conductivity of the plasma and the applied frequency. Such a measurement was carried out at the Plasmadyne laboratory with a plasma jet which was contained in a vycor tube surrounded by a two-turn coil of 7.6 cm. diameter. The coil was part of the 20 to 55 mc. oscillator. The resonance was detected by a radio set. At a resonant frequency of 50 mc. the skin depth was computed to be 0.7 cm. and the conductivity 100 mhos/m. The instrument was calibrated with a standard solution of sulfuric acid.

NASA Plasma-Arc Facilities

The following chapter lists facilities at NASA centers and the closely associated Army Missile Command in a "quick reference" form.

<i>Research Center:</i>	<i>Page</i>
Ames. -----	156
Langley -----	160
Lewis -----	164
NASA Manned Spacecraft Center -----	166
Army Missile Command -----	168

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER
MOFFETT FIELD, CALIFORNIA, 94035

PERSON RESPONSIBLE FOR FACILITY

- (1-4) Bradford Wick
- (5) Magnetoplasmadynamics Branch
- (6) Howard Stine

FACILITY TYPES

- (1) Arc Heated Hypersonic Wind Tunnel (Aero Leg)
- (2) Arc Heated Hypersonic Wind Tunnel (Heat Transfer Leg)
- (3) Arc Heated Hypersonic Wind Tunnel (12" Vertical Jet)
- (4) Arc Heated Supersonic Materials Test Facility
- (5) Constricted-Arc Supersonic Jet
- (6) Plasmadyne Plasma Arc

EQUIPMENT, TEST CAPABILITIES, INSTRUMENTATION, ETC.

- (A) Type Power Supply and Total Power Capability
 - (1) 15 Mw.—Ignitron Rectifier dc Supply
 - (2) Same as (1)
 - (3) 3.75 Mw. ac Supply and 3.75 Mw. dc Motor Generator Set
 - (4) Same as (3)
 - (5) Motor Generator Sets, 1,200 volts, 2,000 amps
 - (6) Transformer—Solid State Rectifier
- (B) Vacuum Equipment
 - (1) 5-Stage steam ejector
 - (2) Same as (1)
 - (3) 19,000 ft.³—Vacuum storage spheres
 - (4) Same as (3)
 - (5) Same as (1)
 - (6) Same as (1)
- (C) Enthalpy Range
 - (1) 600 to 2,000 Btu/lb.
 - (2) 2,000 to 10,000 Btu/lb.
 - (3) 500 to 2,000 Btu/lb.
 - (4) 500 to 7,500 Btu/lb.
 - (5) Average: 5,000 to 30,000 Btu/lb., Centerline: 11,000 to 70,000 Btu/lb.
 - (6) 5,000 to 10,000 Btu/lb.

- (D) Arc Chamber Pressure Range
 - (1) Up to 2,000 psi
 - (2) Up to 150 psi
 - (3) Up to 2,000 psi
 - (4) Up to 75 psi
 - (5) $\frac{1}{4}$ to 2 atmospheres
 - (6) $\frac{1}{2}$ atmosphere
- (E) Plenum (Stagnation) Chamber Pressure Range
 - (1) Up to 2,000 psi
 - (2) Up to 150 psi
 - (3) Up to 2,000 psi
 - (4) Up to 75 psi
 - (5) $\frac{1}{4}$ to 2 atmospheres
 - (6) $\frac{1}{3}$ atmosphere
- (F) Nozzle Exit Diameters
 - (1) 24 in.
 - (2) 4 in. and 24 in.
 - (3) 6 in., 10 in., and 12 in.
 - (4) 2.75 in.
 - (5) 6 in., approximately
 - (6) 4 in.
- (G) Mach Number Range
 - (1) 17
 - (2) 4 to 7
 - (3) 6.5 to 21
 - (4) 3.2 to 4
 - (5) Unknown
 - (6) 5.6 to 5.9
- (H) Nozzle Exit Pressure Range
 - (1) 0.005 to 0.04 mm. Hg
 - (2) 0.015 to 30 mm. Hg
 - (3) 0.004 to 3.0 mm. Hg
 - (4) 2 to 25 mm. Hg
 - (5) 1 mm. Hg (approximately)
 - (6) 0.00035 to 0.0004 atmospheres
- (I) Stagnation Pressure Range
 - (1) 10 mm. Hg
 - (2) 0.8 to 450 mm. Hg
 - (3) 3 to 110 mm. Hg
 - (4) 35 to 520 mm. Hg
 - (5) 2 to 20 mm. Hg
 - (6) 0.015 to 0.0175 atmospheres

(J) Models**(1) Specimen Diameters:**

- (a) Up to 6 in.
- (b) Up to 6 in.
- (c) Up to 3 in.
- (d) Up to 1 in.
- (e) $\frac{3}{4}$ in. max.
- (f) $\frac{3}{4}$ in.

(2) Specimen Shape:

- (a) Variable
- (b) Variable
- (c) Variable
- (d) Variable
- (e) Hemisphere cylinder
- (f) Cones, Hemisphere cylinders

(3) Heat Transfer Rates:

- (a) 3 to 30 Btu/ft.²-sec. depending upon model size
- (b) 10 to 1,600 Btu/ft.²-sec. depending upon model size
- (c) 3 to 120 Btu/ft.²-sec. depending upon model size
- (d) 5 to 1,400 Btu/ft.²-sec. (with radiation and convection heating)
- (e) 100 to 1,000 Btu/ft.²-sec.
- (f) 10 to 250 Btu/ft.²-sec.

(K) Working Gas

- (1) Air
- (2) Air
- (3) Air, nitrogen, and argon
- (4) Air, nitrogen, and argon
- (5) Synthetic air, argon, nitrogen, and carbon dioxide plus nitrogen
- (6) Nitrogen

(L) Gas Flow Rates

- (1) 0.04 to 0.5 lb./sec.
- (2) 0.005 to 0.02 lb./sec.
- (3) 0.005 to 0.05 lb./sec.
- (4) 0.005 to 0.4 lb./sec.
- (5) 0.003 to 0.02 lb./sec.
- (6) 0.005 lb./sec.

(M) Run Time

- (1) Up to 2 min.
- (2) Up to 2 min.
- (3) Up to 1 min.
- (4) Up to 1 min.

- (5) Continuous
- (6) Continuous
- (N) Method of Arc Stabilization
 - (1) Magnetic Field
 - (2) Vortex plus magnetic field
 - (3) Magnetic Field
 - (4) Magnetic Field
 - (5) Wall-stabilized
 - (6) Vortex
- (O) Instrumentation
CEC, Offner, Manometers, Scopes, etc.
- (P) Diagnostic Instrumentation
Calorimeters, Pressure Probes, Glow Discharge, Flow Visualization.
- (Q) Operational Status
 - (1) Operational
 - (2) Being calibrated
 - (3) Operational
 - (4) Operational
 - (5) Operational
 - (6) Operational
- (R) Field of Primary Interest
 - (1) Aerodynamic Testing (i.e., forces, flow fields, and pressures)
 - (2) Materials Testing and aerodynamic characteristics under ablation conditions
 - (3) Aerodynamic Testing
 - (4) Materials Testing
 - (5) Materials Testing
- (S) Available for Outside Testing (Rental Rate)
 - (1-4) Limited testing available
 - (5-6) No
- (T) Reports Available
 - (a) "A Wind Tunnel Using Arc-Heated Air for Mach Numbers from 10 to 20," by Forrest E. Gowan and Vaughn D. Hopkins
 - (b) "Simulation of Convective and Radiative Entry Heating," by John H. Lundell, Warren Winovich, and Roy M. Wakefield
 - (c) "Performance of a Constricted Arc Discharge in a Supersonic Nozzle," by Charles E. Shepard, and Velvin R. Watson. Paper presented at Fifth Biennial Gas Dynamics Symposium, AIAA; Northwestern University, Evanston, Illinois, Paper No. 63-380
 - (d) NASA TN D-1146, D-1889, D-1205

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER
LANGLEY STATION
HAMPTON, VIRGINIA, 23365

PERSON RESPONSIBLE FOR FACILITY

- (1) W. B. Boatright—(1 foot Hypersonic Arc Tunnel)
- (2) E. S. Love, W. B. Boatright—(10 Megawatt Hypersonic Arc—Heated Tunnel)
- (3-4) R. D. Ross (10 Megawatt Arc Tunnel and 2½ Megawatt Arc Tunnel)
- (5) G. M. Stokes (2 Mw. Arc Tunnel)

FACILITY TYPE

- (1) 1-foot Hypersonic Arc Tunnel
- (2) Hyperthermal Leg of 10-Megawatt Hypersonic Arc-Heated Tunnel
- (3) 10-Megawatt Arc Tunnel
 - (a) Phase 1 (current operation)
 - (b) Phase 2 (in operation 1965)
- (4) (a) 2½ Megawatt Arc Tunnel
 - (b) 2½ Megawatt Atmospheric Arc Jet
- (5) 2 Megawatt Arc Tunnel

EQUIPMENT, TEST CAPABILITIES, INSTRUMENTATION, ETC.

- (A) Type Power Supply and Total Power Capability
 - (1) 1.5 megawatts dc (generators)
 - (2) 10 megawatt dc, silicon diode rectifiers (total of 20 megawatts available at later date)
 - (3) (a) 10 megawatt, 3 phase ac (b) 15 Mw. dc
 - (4) (a) (b) 10 megawatt, 3 phase ac
 - (5) Batteries supply 2 Mw. to arc
- (B) Vacuum Equipment
 - (1) 5-stage steam ejector
 - (2) 524,000 ft.³ vacuum sphere (can be evaluated to .1 micron)
 - (3) (a) (b) 117,000 ft.³ sphere
 - (4) (a) Continuously running air ejector (b) none
 - (5) 12,000 ft.³ sphere
- (C) Enthalpy Range
 - (1) Up to 3,000 Btu/lb. (at present)
 - (2) Up to 9,000 Btu/lb. expected

- (3) (a) (b) Up to 3,000 Btu/lb.
- (4) (a) (b) 3,500 Btu/lb. maximum
- (5) 1,500–3,000 Btu/lb.
- (D) Arc Chamber Pressure Range
 - (1) 12 to 30 atmospheres
 - (2) Up to 100 psi
 - (3) (a) (b) 1 to 33 atmospheres
 - (4) (a) 4 atmospheres (b) 1 to 2 atmospheres
 - (5) 6 to 68 atmospheres
- (E) Nozzle Exit Diameter
 - (1) $\frac{1}{8}$ -inch throat, 1-foot test section
 - (2) $\frac{1}{2}$ -inch and $\frac{1}{4}$ -inch dia. throats, 2-foot and 4-foot test section diameters
 - (3) (a) (b) 6, 12, 24 inches
 - (4) (a) 2 inches (b) 1, 2, 4, 6, 12 inches
 - (5) 20 inches
- (F) Mach Number
 - (1) 12
 - (2) 10–19
 - (3) (a) 6.1, 8.1, 10.6 (b) 5.0, 6.1, 7.1
 - (4) (a) 2.65 (b) 1 to 0.04
 - (5) 13.5
- (G) Nozzle Exit Pressure Range
 - (1) Approximately 40 microns
 - (2) 1×10^{-6} to 1×10^{-3} atmospheres
 - (3) (a) 0.06 to 0.0015 psia (b) 0.15 to 0.005 psia
 - (4) (a) 2.40 psia (b) atmospheric
 - (5) 20 to 120 mm. Hg
- (H) Test Section Pressure Range
 - (1) Same as (G)
 - (2) Same as (G)
 - (3) (a) 0.002 psia (b) Same as (G)
 - (4) (a) 1.50 psia (b) Same as (G)
 - (5) Same as (G)
- (I) Stagnation Pressure Range
 - (1) 7 to 9 mm. Hg
 - (2) 0.001 to 0.3 psia
 - (3) (a) 3.8, 0.90, 0.025 psia (b) 4.0, 0.92, 0.03 psia
 - (4) (a) 21 psia (b) up to 2 atmospheres (sonic)
 - (5) 4 to 19 mm. Hg
- (J) Models
 - Specimen Diameters
 - (1) About 2 inches

- (2) Up to 12 inches
- (3) (a) Up to 12 inches (b) Same
- (4) (a) Maximum 3 inches (b) Up to 12 inches
- (5) Up to 5 inches
- Specimen Shapes
- (1-5) As desired
- Heat Transfer Rates:
- (1) 50 Btu/ft.²-sec. on 1-inch dia. hemisphere
- (2) Up to 120 Btu/ft.²-sec. on 1-inch dia. hemisphere
- (3) (a) 170 Btu/ft.²-sec. max. (b) 340 Btu/ft.²-sec. maximum
- (4) (a) 250 Btu/ft.²-sec. on 1-inch dia. flat face (b) Up to 500 Btu/ft.²-sec. on 1-inch dia. flat face
- (5) 25-50 Btu/ft.²-sec. on 2-inch dia. hemisphere
- (K) Working Gas
- (1) Air or nitrogen
- (2) Air
- (3) (a) Air or nitrogen (b) Synthetic air or nitrogen
- (4) Air or nitrogen
- (5) Air
- (L) Gas Flow Rates
- (1) 0.015 to 0.04 lb./sec.
- (2) 0.02 to 2.0 lb./sec.
- (3) (a) 0.50 lb./sec. (b) 0.28 lb./sec.
- (4) (a) (b) Up to 0.45 lb./sec.
- (5) 0.03-0.34 lb./sec.
- (M) Run Time
- (1) Presently about 3 minutes (continuous later)
- (2) 1 to 10 minutes
- (3) (a) (b) 5 minutes
- (4) (a) (b) 1½ hours
- (5) 45 seconds
- (N) Method of Arc Stabilization
- (1) Ballast resistance and magnetic field
- (2) Ballast resistance and magnetic field
- (3) (a) Magnetic field (b) To be determined
- (4) (a) (b) Magnetic field
- (5) Magnetic field
- (O) Instrumentation
- (1) 36 oscillograph channels, 10 alphasatrons, pressure transducers, strip chart potentiometers, camera
- (2) 36 channel oscillograph, 40 alphasatrons, 100 channel automatic tape recording, pressure transducers, 18 channel digital readout

- (3) (a) (b) 42 channels for thermocouples, 24 for wire strata gages, 36 channel oscillograph, 100 channels of automatic tape recording, 80 tube manometer, pressure transducers, high speed cameras
- (4) (a) (b) Same as for the 10 Mw. tunnel
- (5) Temperature and pressure with continuous recording on oscillographs, high speed cameras
- (P) Diagnostic Instrumentation
Total pressure probes, heat transfer probes, enthalpy probe, spectrograph, electron beam
- (Q) Operational Status
 - (1) Operational (undergoing calibration)
 - (2) Under construction, expect calibration tests can begin in fall of 1963
 - (3) (a) Operational 9/1/63 (b) Operational about 1/1/65
 - (4) (a) (b) Operational
 - (5) In calibration
- (R) Field of Primary Interest
 - (1) Hypersonic aerodynamics and heat transfer
 - (2) Hypersonic aerodynamics and heat transfer
 - (3) Materials testing
 - (4) Materials testing
 - (5) Materials testing
- (S) Future Plans
 - (1) Research on facility development as well as fundamental high enthalpy research
 - (2) Water-cooled 4-inch diameter subsonic nozzle to be constructed
- (T) Available for Outside Testing (Rental Rate)
 - (1) Eventually available to government agencies and government contractors after sufficiently calibrated
 - (2) Same as (1)
 - (3) Available to government agencies and government contractors
 - (4) Same as (3)
 - (5) Same as (3)
- (U) Reports Available
TN D-1377, TN D-1621, TN D-1927

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER
21000 BROOKPARK ROAD
CLEVELAND, OHIO, 44135

PERSON RESPONSIBLE FOR FACILITY

J. Perry Campbell

FACILITY TYPES

- (1) Arc Heated Wind Tunnel
- (2) Arc Heated Supersonic Free Jet

EQUIPMENT, TEST CAPABILITIES, INSTRUMENTATION, ETC.

- (A) Type Power Supply and Total Power Capability
 - (1) Motor-generator, six generators each at 600 volts, 1,000 amps
 - (2) Motor-generator, 550 volts, 6,000 amp dc (two 275 volt, 6,000 amp units in series)
- (B) Vacuum Equipment

Approximately 8 mm. absolute, two stage air ejector in conjunction with DeLaval or Roots Exhausters
- (C) Enthalpy Range
 - (1) 2,000-12,500 Btu/lb.
 - (2) 4,000-10,000 Btu/lb.
- (D) Arc Chamber Range
 - (1) 5-15 atmospheres
 - (2) 0.5-3 atmospheres
- (E) Nozzle Exit Diameters
 - (1) 23.3 inches (16.0 inches effective)
 - (2) 2.0 inches
- (F) Mach Number Range
 - (1) 5-8
 - (2) Approximately 3.5 at 8,000 Btu/lb.
- (G) Nozzle Exit Pressure Range
 - (1) 5×10^{-4} to 2.6×10^{-3} atmospheres
 - (2) 8 mm. absolute
- (H) Stagnation Pressure Range
 - (1) 1.2 to 4.3×10^{-2} atmospheres
 - (2) 0.19 to 0.30 atmospheres
- (I) Models
 - (1) Specimen diameters less than 6 inches
- (J) Working Gas

Nitrogen
- (K) Gas Flow Rates
 - (1) 0.1 to 1.0 lb./sec. nitrogen
 - (2) 0.02 lb./sec. nitrogen

- (L) Run Times
 - (1) 5 minutes
 - (2) Continuous
- (M) Method of Arc Stabilization
 - (1) Magnetically spun
 - (2) Magnetically spun
- (N) Instrumentation
 - Recorders, manometers, transducers, oscillograph
- (O) Diagnostic Instrumentation
 - Calorimeters, pressure probes, enthalpy probes
- (P) Operational Status
 - (1) Initial check-out about July 15, 1964
 - (2) Presently in operation
- (Q) Field of Primary Interest
 - Materials testing, energy conversion, magnetohydrodynamic effects
- (R) Available for Outside Testing (Rental Rate)
 - Yes
- (S) Reports Available
 - NASA TN D-1215, NASA TN D-1222

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS, 77001

PERSONS RESPONSIBLE FOR FACILITY

J. N. Kotanchik
D. H. Greenshields

FACILITY TYPE

One-megawatt, Arc Heated Atmospheric Pressure Subsonic
Air Jet

EQUIPMENT, TEST CAPABILITIES, INSTRUMENTATION, ETC.

- (A) Type Power Supply and Total Power Capability
dc power supply with silicon rectifiers and saturable core reactor
control having a total power capability of 1.5 megawatts
- (B) Vacuum Equipment
None
- (C) Enthalpy Range
7,000 to 17,500 Btu/lb.
- (D) Arc Chamber Pressure Range
1 to 3 atmospheres
- (E) Nozzle Exit Diameters
1½ to 3 in.
- (F) Mach Number Range
Subsonic
- (G) Test Section Pressure Range
Jet exhausts to atmosphere
- (H) Stagnation Pressures Range
Jet is subsonic
- (I) Models
 - (1) Specimen Diameters: 1–5 in.
 - (2) Specimen Shape: Hemisphere, flat-faced cylinder, etc.
 - (3) Heat Transfer Rates: 50–700 Btu/ft.²-sec.
- (J) Working Gas
Synthetic air, argon, nitrogen
- (K) Gas Flow Rates
0.008 to 0.067 lb./sec.
- (L) Run Time
10 minutes
- (M) Method of Arc Stabilization
Magnetic-field and gas vortex

- (N) Instrumentation
50 channel digital tape recorder, strip-chart recorders, oscillograph, pressure transducers, optical pyrometer, infrared radiometer
- (O) Diagnostic Instrumentation
Calorimeters, enthalpy probes, spectrograph, heat balance measurements
- (P) Operational Status
This facility became operational in September, 1963
- (Q) Field of Primary Interest
Materials testing, small samples of full-scale spacecraft heat shield systems
- (R) Future Plans
Development of a ten megawatt arc tunnel facility to be used for testing large samples of full-scale spacecraft heat-shield systems under simulated environmental conditions encountered by manned spacecraft during entry and reentry
- (S) Available for Outside Testing (Rental Rate)
This facility will not be used for outside testing.

ARMY MISSILE COMMAND
REDSTONE ARSENAL
HUNTSVILLE, ALABAMA

PERSON RESPONSIBLE

Dr. Thomas A. Barr, Jr.

FACILITY TYPES

- (1) 75 kw. Materials Test Facility
- (2) 8,000 kw. Reentry Simulator (under construction)

EQUIPMENT, TEST CAPABILITIES, INSTRUMENTATION, ETC.

- (A) Type Power Supply and Total Power Capability
M.G. Sets Total 8,000 kw.
- (B) Vacuum Equipment
1,200 CFM Roots Blower, 20" Oil Diffusion Pump, 10,000 Cubic Feet Vacuum Reservoir, "Blank Off" Pressure—.03 Micron Hg.
- (C) Enthalpy Range
 - (1) $h/RT_o = 500$ (75 kw.)
 - (2) $h/RT_o = 150$ (8,000 kw.)
- (D) Arc Chamber Pressure Range
 - (1) 1 to 100 mm. Hg. (75 kw.)
 - (2) 3×10^{-2} to 10 Atmospheres (8,000 kw.)
- (E) Nozzle Exit Diameters
 - (1) 5 cm. (75 kw.)
 - (2) 2 to 7.5 (8,000 kw.)
- (F) Mach Number Range
 - (1) .5 to 2 (75 kw.)
 - (2) 2 to 7.5 (8,000 kw.)
- (G) Nozzle Exit Pressure Range
.03 Microns Hg. to 1,000 Microns Hg.
- (H) Stagnation Pressure Range
Information not available
- (I) Models
Information not available
- (J) Working Gas
Air, Synthetic Air, Argon, Nitrogen, Carbon Dioxide, Helium
- (K) Gas Flow Rates
 - (1) .1 gram/sec.-5 grams/sec. (75 kw.)
 - (2) 3 grams/sec.-500 grams/sec. (8,000 kw.)
- (L) Run Time
 - (1) Indefinite run time (75 kw.)
 - (2) 10 to 20 seconds (8,000 kw.)

(M) Method of Arc Stabilization

- (1) Gas Sheath (75 kw.)
- (2) Magnetic (8,000 kw.)

(N) Instrumentation

Instrumentation is centered around a 192 channel data recording system. The outputs of thermocouples, pressure transducers, spectral radiometers and other instruments are sampled 20 times per second per data channel. Data is recorded on tape and analyzed by a digital computer.

(O) Diagnostic Instrumentation

Electrostatic probes are being used. Heat flux probes and electron beam probes are to be installed. Microwave probes have been used.

(P) Operational Status

The 75 kw. facility has been in working order and in more or less continuous use since mid 1957. The 8,000 kw. facility is now being constructed. Limited operational tests have been made.

(Q) Fields of Primary Interest

Reentry Simulation, Materials Testing, and Basic Plasma Research

(R) Future Plans

Completion of the 8,000 kw. facility is planned for the near future. Its capability and utility will dictate future plans.

(S) Available for Outside Testing (Rental Rate)

No

(T) Reports Available

"The ARGMA Plasma-Jet Facility—A Resumé—1958 to 1960", ARGMA TN 2H2N, dated 1 July, 1961; and "Interim Report on the Design and Construction of the ARGMA 8,000 kw. Plasma Facility", ARGMA TN 2H5N, dated 25 October, 1961.

Bibliography of Arc Jet Technology

The following chapter lists the publications of arc jet work in chronological order. On page 190 begins a listing of NASA sponsored contracts, and on page 193 is a cross index to both contracts and bibliography by author(s). Selected abstracts are included in the bibliography, with special emphasis on those articles difficult to obtain at this time.

BIBLIOGRAPHY WITH SELECTED ABSTRACTS

1. Stuhlinger, E., "Possibilities of Electrical Space Ship Propulsion," paper presented at the V International Astronautical Congress, published by Springer-Verlag, Vienna, 1955.
A study on feasibility and performance of an electrical propulsion system for interplanetary space ships is presented. A propulsion system is proposed in which a suitable propellant (cesium or rubidium) is vaporized and ionized at incandescent platinum surfaces. Ions and electrons are accelerated and expelled at equal rates; they recombine immediately after leaving the thrust chambers. The power for the accelerating fields is obtained from turbo-electric generators. Heat source is the sun. A thermo-electric pile would be about ten times less efficient than a turbo-electric plant with the same total mass. The acceleration of a space ship equipped with an electrical propulsion system is of the order of 4×10^{-5} G. A space ship with payload of 50 tons, a total initial mass of 270 tons, and a total flight time of one year would cover a distance of about 183×10^6 km. if it started with the velocity zero and traveled through space without gravity fields. Application of the results to a ship traveling from an earth satellite orbit to a Mars satellite orbit and back will be presented in a later paper.
2. Stuhlinger, E., "Electric Propulsion System for Space Ships with Nuclear Power Source," *J. Astronautics*, Part I, 2, 149, 1955: Part II, 3, 11, 1956: Part III, 3, 33, 1956.
3. Stuhlinger, E., "The Flight Path of Electrically Propelled Space Ships," *Jet Propulsion*, 27, 4, 410-414, April, 1957.
4. Sager, S. L., and Buhler, R. D., "Plasma Jet Wind Tunnel Ablation Tests of Fiberglas Micarta 259-2," special report prepared by Plasmadyne Corp. under ORD-1032 (ABMA), March 1958. (*1, *2)

*Numbers with asterisk—refer to key numbers at end of Bibliography on p. 200.

5. Sager, S. L., and Buhler, R. D., "Ablation of Nylon and Teflon Models in Air," special report prepared by Plasma-dyne Corp. under ORD-1313, (ABMA) October 1958. (*1, *2)
6. Stuhlinger, E., "Space Travel with Electric Propulsion Systems," paper presented at the Second International Symposium on the Physics and Medicine of the Atmosphere and Space, San Antonio, Texas, November 1958. (*7)
7. Shepard, C. E., and Boldman, D. R., "Preliminary Development of Electrodes for an Electric-Arc Wind Tunnel," NASA Memorandum 4-14-59E, 1959. (*7)

Two electrode configurations were tested in an electric arc wind tunnel at the NASA Lewis Research Center. The results indicated approximately the same heat loss rate per unit of arc power input for each of the configurations. Measured heat loss rates were on the order of 40 percent of the arc power input. Nearly all this loss occurred at the anode. The power input and arc current limitations of the electrodes appear to be the critical design factors. Up to now, the maximum power to the stream has been 115-kilowatts with a cooled tungsten cathode and a cooled cylindrical anode incorporating a magnetic field. The maximum power to the anode could not be established with the cooled tungsten cathode because cathode failures occurred at a gross power level of approximately 175-kilowatts. It was necessary to use a graphite cathode to seek the limitations of the anode. The results indicated that the anode limitation was primarily a function of arc current rather than power input. The anode was successfully operated at a power level of 340-kilowatts at 1730 amperes; however, the anode failed with a power input of 324-kilowatts and a current of 2,140 amperes. The magnetic flux density at the time of failure was 0.32 weber per square centimeter, or 3,200 gauss. The graphite cathode was used only to establish the anode limitation; further investigation of graphite cathodes was discontinued because of the large amount of stream contamination associated with this type of electrode.

8. Stuhlinger, E., "Advanced Propulsion Systems for Space Vehicles," Proceedings of the IX International Astronautical Congress, Amsterdam, published by Springer-Verlag, Vienna, 1959.

Chemical, solar-heated, nuclear-heated, arc-heated, plasma jet and electrostatic ion propulsion systems are compared as to their performance on space vehicles. Chemical systems appear feasible and useful for space missions. Solar- and also nuclear-heated systems are promising only where liquid hydrogen is used as a propellant. Arc-heated systems are less attractive than chemical systems from an overall weight standpoint. Plasma jet systems can provide a high specific impulse, but they need much auxiliary equipment. Electrostatic ion systems appear feasible and attractive from a weight standpoint, as long as accelerations of about 10^{-4} G are acceptable. The decisive figure for the last two systems is the specific power measured in kg. per kw. The exhaust velocity has an optimum value for each given flight mission and specific power. At this optimum exhaust velocity, the total mass of the vehicle is a minimum.

9. Von Jaskowsky, W. F., "Direct Jet Velocity Measurements with Drum Camera," special report prepared by Plasmadyne Corp. under ORD-1313 (ABMA), January 1959. (*1, *2)
10. Buhler, R. D., and Christensen, D., "On the Stable Shape of an Ablating Graphite Body," *Journal of Aerospace Sciences*, 26, 1, January 1959.

11. Grindle, S. L., Christensen, D., and Buhler, R. D., "Development of Arc and Mixing Chambers for Use with Air and Nitrogen," special report prepared by Plasmadyne Corp. under ORD-1032 (ABMA) March 1959. (*1, *2)

Experiments are reported relating to the optimum length and contour for a water-cooled anode to be used with air. The basic electrode configuration is that of a constricted, vortex stabilized blown arc. The power levels for the generator are between 40 and 12-kw., the mass flow rate between 0.001 and 0.01 pound per second, and the pressure (choked exit) between 0.1 and 1 atmosphere.

It was found that for air, it is necessary to have an appreciably longer anode than for argon; and, further, that the required voltage for a given pressure-current level can be reduced by flaring the cylindrical portion of the anode. Also, the flare anode accommodated a much wider range of mass flow values without blowout.

These experiments are part of a continuing effort in this laboratory for the improvement of water-cooled electrodes, mixing chambers, and supersonic nozzles operating with air for reentry simulation arc jet tunnels. The overall goal of these experiments is a set of design criteria for the development of a one-megawatt arc plasma generator and nozzle. The experiments reported here play an important role in this development program.

12. Stuhlinger, E., "Propulsion in Outer Space," paper presented in the Ninth Tripartite AXP Conference, Quebec, Canada, April 1959. (*7)
13. Heller, G., "Propulsion for Space Vehicles by the Thermodynamic Process," paper presented at the Ninth Tripartite AXP Conference, Quebec, Canada, May 1959. (*8)

Existing propulsion systems for missiles and rockets use an open thermodynamic cycle. Hot gasses are emptied in an adiabatic-isentropic process in a convergent-divergent nozzle. The process is characterized by its simplicity. The hot fluid is obtained by chemical reaction of one or two liquid propellants or of one solid propellant in the combustion chamber by an isobaric type reaction. Constant pressure is maintained by choking in the throat. The intent of this paper is to discuss the process specifically with respect to its application to propulsion of space vehicles. Other than chemical energy sources are included in the discussion.

14. Stuhlinger, E., "Lunar Ferry with Electric Propulsion System," paper presented at the Annual Meeting of Japanese Rocket Society, Tokyo, Japan, May 1959. (*7)
15. Jahn, R. G., and Von Jaskowsky, W. F., "Langmuir Probe Measurements in the Plasma Tunnel," special report prepared by the Plasmadyne Corp. under ORD-1313 (ABMA) August 1959. (*1, *2)

Recently a further series of probe measurements was taken in the argon plasma jet tunnel in order to investigate the following problems associated with probe measurements.

1. Plasma potential and plasma jet electrode polarity.
2. Probe heating effects.
3. Radial survey of the floating potential in the jet.
4. Effects of the probe holder.

In addition, the theory of the plane Langmuir probe has been elaborated to be appropriate to the experimental situations.

In this report, data are submitted and discussed from thirteen of the probe runs for the purpose of recording and extending the results first presented in the report of 29 January 1959. The Appendix outlines some phases of the theoretical program.

16. Bucher, G., "Electric Propulsion Systems for Satellite Orbit Corrections," ABMA Report No. DV-TN-24-59, August 1959. (*2)
17. Christensen, D., and Buhler, R. D., "Arc Jet Measurements Related to Ablation Test Validity," special report prepared by the Plasmadyne Corp. under ABMA ORD-1872 for presentation at ASTM National Meeting, San Francisco, California, October 1959; ASTM Special Technical Publication No. 279, 1960. (*1, *2)

The urgent need in recent years for high temperature materials test data has prompted the use of various high-temperature testing facilities, such as arc jets, before these facilities have been thoroughly calibrated. Thus far, the emphasis has been on attaining a high temperature flow which would correspond in a rough way to some free-flight condition without being too concerned about the detailed physical and chemical state of the gas. In this paper, the necessity of obtaining a more accurate description and understanding of the flow is emphasized. This is important not only for gaining a deeper insight into the behavior of materials in high-temperature environments and the nature of the ablation process, but also for attaining a more precise flight simulation. Two questions are also discussed in this paper, namely:

1. How closely can any given free-flight environment be duplicated both on full-size and on scaled-down models?
2. What measurements need to be made in the jet and to what accuracy to calibrate and understand the environment sufficiently well for materials work?

The problem of scaling arises in all those tests where the actual free-flight point is to be simulated. Tunnel costs and power requirements preclude the testing of full-scale parts in many cases. Unfortunately, for ablation testing the attainment of complete dynamic similarity on a scale model appears impossible even in principle (apart from technical difficulties), as will be shown. Only some of the essential dimensionless and dimensional parameters can be matched to the full-scale free-flight case. Others will be off by appreciable factors, and their effect on the test results must be estimated and corrected.

18. Heller, G., "The Plasma Jet as an Electric Propulsion System for Space Applications," paper presented at the American Rocket Society Meeting, Washington, D.C., November 1959. (*8)
19. Stuhlinger, E., "How Useful are Low-Thrust Space Vehicles," paper presented at the American Rocket Society Annual Meeting, Washington, D.C., November 1959.
20. Roberts, T. G., and Hales, W. L., "Spectroscopic Analysis of the Plasma Jet Arc Column," ARGMA TN 1CIN-23, 21-35, December 1959. (*9)
21. Roberts, T. G., "Selected Topics on the Development of Hyperthermal Test Facility," published in the Proceedings of the Third High Temperature Inorganic Refractory Coatings Working Group, San Diego, California: (published as a Technical Documentary Report, Wright-Patterson Air Force Base, Ohio, 1960).

This resumé contains reprints from articles from the "Research Laboratory Quarterly Research Review" Nos. 14, 17, 18, 19, 20, 22, and 23,

representing work done by the Ordnance Missile Laboratories Division of the Army Rocket and Guided Missile Agency Laboratories between 1 May 1957 and 31 October 1959. This is all work leading to the development of a hyperthermal test facility.

22. Stuhlinger E., "Electric Propulsion," *Handbook of Astronautical Engineering* Section IVE2 (Edited by H. H. Koelle), McGraw-Hill Book Co., New York, 1960.

The term "electric propulsion system" is used in connection with a great variety of systems applicable to the propulsion of spacecraft. All electrical propulsion systems, in the same way as chemical, nuclear, hot water, or photon propulsion systems, are based on Newton's theorem of action and reaction. Electric propulsion systems are characterized by the use of electric energy for the ejection of the propellant mass. The accelerating forces may be exerted upon the propellant particles by electrically heated surfaces. Each of these systems requires a source of electric power on board the vehicle. Besides this common feature, the various electric propulsion systems differ very decisively in a number of details. It is advisable, therefore, to differentiate between electrostatic or ion systems, magnetofluid-dynamic systems, and electrically heated systems (which include arc jet systems).

23. Thom, K., and Norwood, J., Jr., "Magnetic Ignition of a High-Voltage Mega-ampere Low-Pressure Discharge," paper presented at the American Physics Society Meeting, Gatlinburg, Tenn., November 1960.
24. Roberts, T. G., Summers, N. B., and Murphy, C. G., "Time Resolved Spectra of a 40,000 Joule Discharge in Argon," ARGMA TN 1CIN-24, 35-41, March 1960. (*9)
25. Roberts, T. G., and Hales, W. L., "Studies on the Electromagnetic Radiation from a Fully Ionized Plasma Device," paper presented at the American Physics Society (SES), April 1960.
26. Seitz, R. N., "Propulsion Systems for Space Flight Applications," lectures given as part of a graduate course in space technology at Washington University, April-May 1960 (published by McGraw-Hill, 1963).
27. Roberts, T. G., and Hales, W. L., "Simulation of the Electromagnetic Radiation Pulse from a Nuclear Explosion at High Altitude," paper presented at 2nd Symposium of Ordnance Physics OOR, Duke University, Durham, N.C., May 1960. (*9)
28. Shepard, C. E., "A Résumé of Electrode Development at NASA Lewis," Inter-Center NASA Conference on Magneto Gasdynamic Research, Lewis Research Center, June 1960 (*3)

The program to develop suitable electrodes for an electric arc heated hypervelocity wind tunnel began early in 1957. Graphite electrodes were used in the first device; however, the stream contamination was very high. Attempts were made to minimize the loss of carbon into the stream by venting the carbon rich atmosphere near the anode rod. This was helpful in reducing the contamination, but the tube either became clogged with soot or, if uncooled, quickly overheated and failed. Transpiration cooling of a graphite rod was also unsuccessful at Lewis, although others have been able to operate at moderate power levels with very low contamination.

29. Jahn, R. G., and Von Jaskowsky, W. F., "Shielded Langmuir Probe Measurements in the Plasma Jet," special report prepared by the Plasmadyne Corp. under ORD-1313 (ABMA), June 1960 (*1,*2)

Electron density and temperature determinations with a Langmuir type electronic probe in a supersonic hot argon jet have been extended. The recent measurements utilize plane circular probes fitted with electrostatic guard rings maintained at the same potential as the probe. One probe is oriented normal to the jet flow, and thereby is exposed to the stagnation point boundary layer behind a bow shock. In another experiment, a similar guarded probe is imbedded in a flat plate parallel to the flow, hence is covered by the viscous boundary layer on the plate. The resulting voltage current characteristics are analyzed on the basis of the elementary probe theory to yield electron temperatures and densities. The electron temperatures are found to be quite high, more appropriate to the core of the arc itself than to the free stream or stagnation temperatures in the jet, thereby emphasizing the inefficiency of the electron energy transfer in the argon plasma. The electron densities, on the other hand, are found to be only slightly higher than those predicated by the Saha equilibrium theory for the jet. The effects of probe heating and contamination are discussed.

30. Hess, R. V., "Experiments and Theory for Continuous Steady Acceleration of Low Density Plasmas," paper presented at the XI International Astronautical Congress, Stockholm, Sweden, August, 1960. Published by Springer-Verlag, Vienna, Vol. I of Proceedings, 404-411, 1961.

Continuous plasma acceleration has been experimentally achieved between coaxial electrodes with the use of magnetic field gradients. The axial component of the magnetic field aids in ionizing the gas by lengthening the path of the electrons for collisions, as in the Phillips ionization gauge. The axial component is also instrumental in the axial plasma acceleration. It interacts with the radial current to produce a circular component of electron motion exceeding by far that of the ions, particularly at low densities. The circular Hall currents, together with the radial component of the magnetic field, cause an axial force for plasma acceleration. The circular currents interacting with the axial magnetic field component cause an inward confining force on the plasma. For higher densities, the whole plasma is set in rotation. The circular currents yielding acceleration and confinement of the plasma are due to centrifugal forces pushing the plasma against the magnetic field.

31. Stuhlinger, E., "Progress in Electric Propulsion Systems," paper presented at the XI International Congress, Stockholm, Sweden, August 1960. (*7)

The transportation capability of propulsion systems with separate power source, expressed by payload ratio, terminal velocity, and acceleration, depends primarily on two basic parameters: the specific power of the system, α , and the total time of propulsion, τ . Highest terminal velocities to be expected with present technologies are 150-200 km./sec.; highest accelerations 5×10^{-4} G. The payload ratio depends on the specific mission; it may vary in typical cases between 5 and 95 percent.

Electrothermal or arc-heated systems will operate at exhaust velocities of 10 to 15 km./sec. ($I_{sp}=1,000$ to 1,500 sec.); they may find application for satellite correction, orbital freight transfer, and lunar freight missions. Electrostatic or ion systems will have exhaust velocities between 40 and 150 km./sec. ($I_{sp}=4,000$ to 15,000 sec.); they will be useful for lunar freight missions, for unmanned and manned planetary flight, and for deep space probes. Electrodynamic and MFM systems promise to cover a wide range of exhaust velocities from 10 to 1,000 km./sec. ($I_{sp}=1,000$ to 100,000 sec.).

Their technology is not yet developed far enough to encourage the design of an operable propulsion system. Flight tests of the other two systems may begin around 1962 to 1964.

32. Roberts, T. G., and Hales, W. L., "Spectroscopic Measurements in a Plasma Jet," ARGMA TN 2HIN-26, 45-48, September 1960. (*9)
33. Jahn, R. G., and Von Jaskowsky, W. F., "Spectroscopic Investigation of the Plasma State," Special Report Prepared by the Plasmadyne Corp. under ORD-1872 (ABMA), November 1960. (*1, *2)

A small experimental arc and jet chamber with side windows was constructed specifically for this experiment. The pressure in both the arc chamber and the jet chamber could be adjusted from above atmospheric pressure to a relatively low vacuum. Plasmas of argon and nitrogen were studied spectroscopically in both the arc and the ensuing plasma jet. (The procedure consisted of simultaneously recording the intensities at four spectral locations of the emitted radiation; two spectral lines and two narrow spectral regions of brems and recombination radiation.) A rotating mirror scanned the optical path transversely through the arc of the jet, and the resulting intensity profiles were displayed.

The system was calibrated by simultaneously recording the intensities from a standard lamp at the four mentioned spectral locations. From the calibrated intensity record, traces of the various radially reduced intensities were obtained by the use of an approximate analytical method instead of the usual numerical integration.

The plasma device was run from a welding arc power supply whose 360 cycle fluctuations could be observed in the intensity profiles. However, these fluctuations were small relative to the total height of the profile, and were averaged out during the reduction of the data. Higher frequency oscillations were filtered out with RC filters between the multiplier tubes and the oscilloscope.

34. Hess, R. V., "Plasma Propulsion," paper presented for publication in Missile Design Development, 1961.
35. Winkler, E. L., and Griffin, R. N., "Effects of Surface Recombination on Heat Transfer to Bodies in a High Enthalpy Stream of Partially Dissociated Nitrogen," NASN TN D-1146, 1961. (*4)

Heat transfer rates to two surfaces having widely different catalytic effectiveness are compared at a Mach number of 6 in a low density stream of partially dissociated nitrogen. The heat transfer rate to polished copper is twice as great as the heat transfer rate to a silicon monoxide coated cylinder when the stream total energy content is 9,000 Btu per pound. Various methods for determining the stream energy content, the stream velocity and the stream Mach number have been developed and compared. It is shown that methods for estimating the stream energy content by means of purely aerodynamic concepts may neglect the sizable fraction of the stream energy contained in molecular dissociation.

36. Hales, W. L., and Roberts, T. G., "f-Value Determination from Nonequilibrium Sources," ARGMA TN 2HIN-28, 81-85, March 1961. (*9)

In most experiments for the determination of f-values it is necessary to assume that the source is in thermodynamic equilibrium in order that the relative populations of the energy levels can be predicted. In some of the most convenient sources of spectral lines, such as hollow-cathode discharge tubes, radio-frequency discharge tubes, and plasma jets, thermodynamic equilibrium does not exist. If two spectral lines originate in the same

energy level, and therefore in identical populations, the relative intensities are directly proportional to the Einstein transition probabilities and are independent of equilibrium, and these quantities can be measured.

37. Roberts, T. G., and Hales, W. L., "Investigation of the Hollow Cathode Discharge as a Source for the Determination of f-Values," ARGMA TN 2HIN-28, 73-81, March 1961. (*9)

An experiment has been performed to determine the usefulness of the hollow cathode discharge tube for measurement of high-excitation f-values. In addition to the obvious usefulness of f-values in astrophysical problems, spectral analysis, and plasma temperature determinations, accurately measured f-values would be very useful to the theoretician in indicating the correctness of the class of the approximate wave function. For example, the f-values could be used to determine whether to utilize the Hartree-Fock wave function or the self-consistent field approximation with or without exchange in a given problem.

38. Harrison, H., "Survey of Electromagnetic Propulsion," paper presented at the American Rocket Society Space Nuclear Conference, April 1961.
39. Hess, R. V., Burlock, J., Seiver, J. R. and Brockman, P., "Theory and Experiments for the Role of Space-Charge in Plasma Acceleration," paper presented at the Symposium on Electromagnetics and Fluid Dynamics of Gaseous Plasma, Polytechnic Institute of Brooklyn, April 1961.

The role of space charge in plasma acceleration is discussed for a variety of accelerator designs. It is shown that the effects of space charges and eddy currents are coupled to each other and the effects on plasma acceleration are discussed. Experimental studies on a coaxial plasma acceleration device reveal the role of space charges in building up oscillations and extra diffusion mechanisms. The possible role of space charge in obtaining electron emission from cathodes above the thermionic level without arc spots is experimentally demonstrated for the so-called hollow cathode configuration.

40. King, J. C., "Some Basic Factors Influencing the Selection of Propulsion Systems for Space Missions," MSFC Report MTP-M-RP-61-9, April 1961. (*6)
41. Roberts, T. G., and Hales, W. L., "A Resonance Type Mechanism for Producing the 4685, 7 Å Line in Plasmas Below 20,000° K.," paper presented at the American Physics Society (SES), Louisville, Ky., April 1961.
42. Stuhlinger, E., "Development and Flight Testing of Electric Propulsion Systems," paper presented at Joint USAF-NASA Meeting on Electrostatic Propulsion, Space Technology Labs, Los Angeles, Calif., April 1961. (*7)
43. Heller, G., and Jones, B. P., "Survey of Arc Propulsion," paper presented at the Space-Nuclear Conference, Gatlinburg, Tenn., May 1961.
44. Stuhlinger, E., "Electric Propulsion Development Program," paper presented at ARS Space-Nuclear Conference, Gatlinburg, Tenn., May 1961. (*7)

The present paper will be restricted to a description of the development of electric systems as it is planned for the next few years.

For this discussion it will be convenient to retain the subdivision of electric systems into electro-thermal or arc-jet engines, electro-static or ion engines, and electrodynamic or MFM (magneto-fluid-mechanic) engines. In each case, there will be five distinct phases which characterize the development program: the component research and development, the laboratory model, the flight model, the flight testing, and the mission phase. Each of the three systems will be represented by a number of different

types of engines; each of these different types will go through the first phase, and some of them will go through all five phases. It should be expected, therefore, that a variety of components and engines will be found in different phases of their development at any time during the next few years.

Electro-thermal or arc jet engines are farthest advanced in their development. One contact with the Plasmadyne Corporation has the objective of providing a one-kw. flight model for a short time flight test in late 1962. If successful, this model may lead to an early application of arc-heated systems for the position and attitude control of satellites.

Electrothermal engines will develop specific impulses of the order of 1,000 to 2,000 seconds. While definitely above those of chemical rocket motors, these specific impulses do not yet provide the substantial saving in propellant mass which will be obtained with electrostatic and electrodynamic systems. For this reason, the usefulness of electro-thermal systems will be predicted on the existence of an electric power supply which is needed on board the spacecraft for other purposes, such as communications or orbital operations. In that case, the power supply can be used with advantage to energize an electro-thermal thruster for limited periods of time.

45. Jack, J. R., "Regenerative and Radiation Cooling of Electro-thermal Thrust Generators," paper presented at the IAS/ARS meeting, Los Angeles, California, June 1961.
46. Martinek F., Vaughn, G. F., and Geideman, W. A., Jr., "Dynamics of Arc Jet System," General Electric Company, paper presented at IAS/ARS meeting, Los Angeles, California June 1961.
47. Barr, T. A., Cason, C. M., Roberts, T. G., and Hales, W. L., "The ARGMA Plasma-Jet Facility—A Resume—1958 to 1960," ARGMA TN 2H2N, July 1961. (*9)
- The ARGMA plasma-jet facility, first put into operation in January, 1958, was constructed for three distinct research functions: to provide information on the design of arc gas heaters, to develop experimental techniques for the measurement of plasma properties, and to screen materials for high temperature applications in rockets and reentry vehicles. The ARGMA plasma jet is a device consisting of a graphite nozzle which also serves as an anode, a praphite rod cathode which is inserted in the upstream convergent section of the nozzle, a 75-kilowatt (nominal maximum power) direct current generator with controls, and an appropriate gas pumping system. This report is a compilation of the research on the ARGMA plasma jet for the period January, 1958 to December 1960.
48. Grisaffe, S. J., "A Preliminary Investigation of the Thermal History of Powder Particles During Plasma Spraying," paper presented at the Fifth Meeting of Refractory Composites Working Group, Dallas, Texas (published as a Technical Documentary Report by Wright-Patterson Air Force Base, Ohio) August 1961.
49. Hayes, R. J., "Bringing in Electrical Propulsion," *Astronautics* 100-106, July 1961.
50. Hales, W. L., and Roberts, T. G., "Determination of f-Values in a Spark Discharge," ARGMA TN 2HIN-29, August 1961.

Previous f-value measurements made at this laboratory required the use of a spectral source which gave lines on the linear portion of the curve

of growth. In a spark discharge, the lines may exhibit strong self-absorption. If the lines are not on the linear portion of the curve of growth, the formulas relating the f -values may be derived directly from Lambert's law.

51. Heller, G., "The Electric Engine as a Propulsion System for the Exploration of Space," paper presented at the International Symposium on Space Age Astronomy, California Institute of Technology, August 1961. (*8)
52. Roberts, T. G., Hales, W. L., and Brandt, R. A., "Effects of a Magnetic Field on the Arc Characteristics of a Plasma Jet," ARGMA TN 2HIN-29 39-47, August 1961. (*9)

The service life of a plasma jet system is determined primarily by the magnitude of the current carried by the electrodes, that is, the current density. If the resistance of the arc is increased, a given amount of power may be delivered to the gas at a lower current density, thus creating a longer life for the electrodes of the plasma head. This increase in resistance may also be used to increase the maximum power which may be delivered to a particular plasma jet head without destroying it.

53. Senn, J. C., and Porter, M., "Radio Frequency Interference Tests on Plasmadyne Arc Plasma Thrusters," Genistron Corp., Test Report TR-928-3227, August 1961.

Tests were performed to determine the radio frequency generation characteristics of Plasmadyne Arc Thrusters. Conducted interference readings from 30 cycles to 100-mc. were required on the dc power line to the arc. Radiated interference measurements were required from 100-mcs. to 10 kmc. In addition, measurements were required inside the test chamber over the ranges 240-260 and 400-420 mc. to gather more specific data on possible influences on telemetering and command communications systems. Internal measurements at these frequencies were required because of the predicted attenuation of signals between the source in the test chamber and external antennas.

54. Noeske, H. O., and Kassner, R. R., "Analytical Investigation of a Bipropellant Arc Jet," paper presented at the ARS Space Flight Report to the Nation, New York, October 1961.
55. Roberts, T. G., Hales, W. L., and Barr, T. A., Jr., "A Spark Discharge for Weapons Effects Simulation," ARGMA TR 2H2R, October 1961.

A fully ionized plasma device of the linear pinch type for the production of gases at extremely high temperature has been designed, constructed and tested. The facility was constructed to determine the feasibility of using the high intensity, short-duration radiation pulse from a high current linear pinch discharge to simulate certain weapons effects.

The effects to be simulated are those caused by the thermal radiation from high-altitude, high-energy explosions. Exact duplication of the radiation spectrum of such explosions has not been attempted in the experiments reported here. For this work, the radiation from the spark discharge was considered adequate if the pulse duration and energy flux were comparable to those of the explosion being simulated.

56. Stuhlinger, E., Hayes, R. J., and Hoffman, M. A., "The Manned Electric Rocket Challenge," paper presented at the ARS Space Flight Report to the Nation, New York, October 1961. (*7)
57. Jack, J. R., "Theoretical Performance of Propellants Suitable for Electrothermal Jet Engines," NASA TN D-682, *ARS Journal*, 31, 12, 1683-1685, December 1961.

58. Kotanchik, J. N., and Ross, R. D., "Electric Arc-Powered Research Facilities for Materials and Structures Testing," ASME paper presented to the Annual Winter Meeting, December 1961.

The electric arc-powered research facilities of NASA at the Langley Research Center which employ alternating current arcs are reviewed. These facilities include arc-powered jets, subsonic arc-tunnels, and hypersonic arc-tunnels up to 10,000-kw. power rating.

Progress made in solving two limitations of arc facilities—running time and contamination of air stream—are described. Some measurement techniques in arc heated air are also discussed.

The use of electric arc facilities in experimental research on materials is shown and some research results for ablation materials are presented.

59. Shepard, C. E., and Winovich, W., "Electric-Arc Jets for Producing Gas Streams with Negligible Contamination," paper presented at the ASME Plasma Jet Symposium, December 1961.
60. Stuhlinger, E., and Urban, E., "Electric Propulsion—A Status Report," *Astronautics*, 6, No. 12, 38, December 1961.
61. Roberts, T. G., and Hales, W. L., "Radiative Transition Probabilities of Calcium," AMC Report RR-TR-62-4, 47-50, December 1961. (*9)

Experimentally determined transition probabilities of the f-values do not exist for the alkali-like ions of the alkaline earths. These constants have been calculated by utilizing the Coulomb approximation of Bates and Damgaard.

Transition probabilities and f-values were also calculated for Calcium I and compared with experimental values. This comparison showed that the approximation of Bates and Damgaard can be used to obtain relative values of these constants even for complex atomic systems. To further illustrate this point, the calculated and the existing experimental f-values for the heavy cesium atom have been used to show the usefulness of the f-values calculated by the Coulomb approximation. Therefore, it is concluded that reasonably accurate relative transition probabilities of f-values can be readily computed by utilizing the tables of Bates and Damgaard along with those of White and Elliasen and those of Goldberg.

62. Roberts, T. G., and Hales, W. L., "Final Report—Transition Probabilities and f-values of the Elements," NASA-H-6710, 1962. (*9)
63. Gowen, F. E., and Hopkins, V. D., "A Wind Tunnel Using Arc-Heated Air for Mach Numbers 10 to 20," proceedings of the Second Symposium on Hypervelocity Techniques, Plenum Press, New York, 1962.

This paper describes a hypersonic wind tunnel for Mach numbers from 10 to 20. The air stream is heated by an arc heater to enthalpies in excess of that required to prevent condensation, but less than flight enthalpy. Some of the instrumentation used with the tunnel is described along with a discussion of limitations imposed upon the performance of such tunnels and problems associated with extending operation to higher pressures and enthalpies.

64. Hess, R. V., "Fundamentals of Plasma Interaction with Electric and Magnetic Fields," NASA University Conference, 1962.
65. Stine, H. A., and Watson, V. R., "Theoretical Enthalpy Distribution of Air in Steady Flow Along the Axis of the Direct-Current Electric Arc," NASA TN D-1313, 1962. (*4)

An approximate solution is obtained for the enthalpy and electrical conductivity distributions in a cylindrical, direct-current-arc column with

steady flow along the axis. The only form of energy loss considered is lateral heat conduction. The solution predicts the following behavior for given length and diameter of column: (1) higher operating efficiencies at lower pressures and higher mass flows; (2) higher enthalpies at higher currents and lower flow rates, and (3) higher arc voltages with higher mass flows. The solution furthermore indicates: that with given mass flow rate, pressure, and current, higher enthalpies occur with increase of length and decrease of radius of the column, that there are simultaneous increases in arc voltages and radial heat transfer, and that the efficiencies will suffer decreases. What has been said with regard to trends with length at fixed mass flow is equivalent to trends with the reciprocal of the mass flow at fixed length. The trend of increasing enthalpy output as radius is decreased agrees with experiment.

66. Winkler, E. L., and Griffin, R. N., "Measurements in a Frozen, Partially Dissociated, High-Speed Gas Stream," proceedings of the Second Symposium on Hypervelocity Techniques, Plenum Press, New York, 1962.

This investigation was undertaken to develop methods of evaluating the performance of arc-heated wind tunnels. Since the type and quantity of species present in the gas stream are not precisely known, it was decided to measure the stream energy content by as many independent ways as possible and to attempt to deduce the stream energy content by comparison of the results. The various methods used were: (1) the average gross energy content was determined from a gross energy balance of the system; (2) the energy content was deduced from measurements of the cold gas rate and the stagnation chamber pressure by calculating what the average energy content of the gas would have to be for the flow to pass through the nozzle throat at the measured rate; (3) the energy content of the stream was deduced from the stagnation region heating rates on a model placed on the stream; (4) the average energy content in the core of the assumed mathematical flow model was deduced from measurements of stagnation, impact, and free-stream static pressures.

67. Gates, D. W., "Materials Requirements for Plasma Propulsion," paper presented at the Golden Gate Metals Conference, San Francisco, California, February 1962.
68. McGee, H., Jr., and Heller, G., "Plasma Thermodynamics I: Properties of Hydrogen, Helium, and Lithium as Pure Elemental Plasmas," paper presented at the Annual ARS Meeting, New York, 1960, published in *ARS Journal*, 32, 2, 203, February 1962.
69. Boehm, R., and Cagle, E., "Power Source for a One-Kilowatt Arc Engine Test Capsule," paper presented at the ARS Meeting in Berkeley, California, March 1962. Submitted for publication to *ARS Journal*, February 1963.
70. Gates, D. W., and McKenna, Q. H., "Materials Problems Related to Arc Jet Thrusters," ARS Electric Propulsion Conference, Berkeley, California, March 1962.

An outline of the criteria on which the selection of materials for an electric arc jet engine is based is given. Potentially useful materials which might serve as electrodes, electrical insulators, and assembly housings are listed based on their properties, availability, and fabricability.

71. Greco, R. V., and Stoner, W. A., "Research and Development of a 1-kw. Plasma Jet Thruster," paper presented at the ARS Meeting in Berkeley, California, March 1962.

Work is reported on the development of a small arc plasma jet thruster suitable for attitude control and orbit adjustment. This work represents the first phase of a program defined by NASA contract NAS5-651 and its extensions which will result in a qualified plasma arc propulsion system in the near future.

The effort to date has resulted in a thruster capable of delivering the required thrust (0.01 lbs.) at a specific impulse in excess of 1,100 seconds. Kinetic efficiencies in excess of 35 percent have been obtained. The above performance was obtained using hydrogen as a propellant. The specific design, along with other designs tested, are reported herein. Some design considerations pertinent to small plasma jet thrusters are presented.

72. Mayo, R. F., and Davis, D. D., Jr., "Magnetically Diffused Radial Electric-Arc Air Heater Employing Water-Cooled Copper Electrodes," paper presented at the ARS Electric Propulsion Conference, Berkeley, California, March 1962. (*10)

A magnetically rotated electric arc air heater has been developed that is novel in that an intense magnetic field of the order of 10,000 to 25,000 gauss is employed. This field is supplied by a coil that is connected in series with the arc. Experimentation with this heater has shown that the presence of an intense magnetic field transverse to the arc results in diffusion of the arc and that the arc has a positive effective resistance. With the field coil in series with the arc, highly stable arc operation is obtained from a battery power supply. External ballast is not required to stabilize the arc when it is operating at maximum power level. The electrode erosion rate is so low that the air stream contamination is no more than 0.05 percent and may be substantially less.

73. Page, R. J., and Humpal, H., "The Objectives and Design of a 1-kw, Arc Engine for Space Flight Testing," paper presented at the ARS Meeting in Berkeley, California, March 1962. (*10)

This paper covers an analytical and experimental program of the objectives of flight testing and the design considerations of a 1-kw. plasma jet flight test engine ultimately suitable for attitude/orbit control of spacecraft in the 1965 period. The relationship of the flight test engine design philosophy to the final attitude/orbit control system is discussed. The choices of propellant, storage, and feed system, as well as electric power adaptation and starting system, are treated.

Hydrogen and ammonia propellants are compared as a function of mission time using the current advances in technology. The benefits of supercritical hydrogen storage in the small sizes and the general lack of zero gravity feed problems are discussed. The flight test engine storage and feed system is described.

Recent advances are reported in efficient power adaptation, by Plasma-dyne and Marshall Space Flight Center, of an arc to power source using constant current controls. A new, simple technique for making, experimentally, over 7,000 consecutive successful starts with noticeable erosion is described.

74. Jones, R. E., and Palmer, R. W., "Traveling Wave Plasma Engine Program at NASA Lewis Research Center," paper presented at the Third Annual Conference on Engineering Magnetohydrodynamics, University of Rochester, Rochester, New York, March 1962.

75. Richter, R., "Development Work on Plasma Arc Jet Engines," paper presented at the ARS Electric Propulsion Conference, Berkeley, California,

- March 1962, published in "Progress in Astronautics and Aeronautics—Vol. 9, Electric Propulsion Development," ed. E. Stuhlinger, Academic Press, New York, 21-42, 1963.
76. Shelton, R. D., Johnson, W. G., Jones, B. P., and King, J. C., "A Performance Analysis of Electrical Propulsion Systems," von Braun Anniversary Volume, March 1962, published by McGraw-Hill, April 1963.
 77. Stuhlinger, E., "Electric Propulsion for Space Flight," paper presented at ceremony during which the Galabert Prize for 1961 was awarded, Paris, France, March 1962. (*7)
 78. Stuhlinger, E., and King, J. C., "Concept for a Manned Mars Expedition with Electrically Propelled Vehicles," paper presented at ARS Electric Propulsion Conference, Berkeley, California, March 1962. (*10)
 79. Stuhlinger, E., Seitz, R. N., Bucher, G., and Heller, G., "Electric Propulsion—A New Technology," von Braun Anniversary Volume, March 1962, published by McGraw-Hill, April 1963.
 80. Boldman, D. R., Shepard, C. E., and Fakan, J. C., "Electrode Configurations for a Wind-Tunnel Heater Incorporating the Magnetically-Spun Electric Arc," NASA TN D-1222, April 1962. (*3)

Various arc heater configurations were tested over a range of nitrogen flow rates, power levels and pressures. Results of an evaluation of arc heater composed of a 0.75-inch thoriated-tungsten cathode, a cylindrical copper anode, and a magnetic field coil are presented. A study to determine the independent effect of pressure on arc potential difference, heater efficiency, and stagnation enthalpy was conducted with this unit using a series of nozzles with throat diameters of 0.5, 0.25 and 0.125 inch. The arc potential difference was essentially independent of the pressure level except for any change in the operating mode. A change in the arc operating mode resulting in a transition to a higher arc potential difference was observed between the flow rates of 0.0055 and 0.0075 pound per second using the 0.25-inch-throat-diameter-nozzle. The highest values of stagnation enthalpy and arc heater efficiency were observed at the conditions corresponding to the highest arc potential difference.

Results are also presented for a higher power heater compounded of three 0.5-inch diameter tungsten cathodes and the aforementioned anode with the magnetic field coil. A plenum and a 0.5-inch-throat-diameter-critical-flow nozzle were incorporated in this latter unit. A correlation of experimental values of stagnation enthalpy with the theoretical-equilibrium and frozen flow values was attempted, however, the correlation was relatively poor because little was known about the actual flow process.

81. Boldman, D. R., "Performance Evaluation of a Magnetically-Spun d.c. Arc Operating in Nitrogen," paper presented at the ARS Electric Propulsion Conference, Berkeley, California, March 1962, AIAA Journal, Vol. 1 #4, 802-805, April 1963.

The results of an experimental investigation of a concentric cylinder type electrode configuration incorporating a magnetic field indicated the arc potential difference in nitrogen was essentially indifferent of the pressure in the range of 1-7 atmospheres except for a specific range of operating conditions in which a 26-percent increase in arc potential difference was obtained. Highest efficiencies were achieved during the high potential operating mode.

The independent effect of the electromagnetic force on the arc is not conclusive; however, experiments in which the magnetic field strength was varied over a moderate range indicated the importance of optimizing this effect both from the standpoint of chamber efficiency and arc stability. Photographs of the arc reveal some of the effects of varying the magnetic field strength. The arc chamber efficiency was also influenced by the flow injection mode. An increase in efficiency was obtained when the flow opposed or was normal to the direction of the Lorentz flow.

82. Roberts, T. G., and Phillips, W., "Measurement of Gas Velocity in a Plasma Jet," paper presented to Symposium of Theoretical and Applied Plasma Physics, Redstone Arsenal, Alabama, May 1962.
83. Goodwin, G., "Production and Diagnostics of Hypervelocity Low-Density Streams," *Troisième Symposium International Sur La Dynamique Des Gaz Raréfies*, Paris, France, June 1962.

Present arc-heater technology has advanced to the point where energy content near that or corresponding to satellite speed in either oxidizing or nonoxidizing gases can be produced. These arc heaters may be operated at sufficiently high pressure to produce Mach numbers in the 7 to 10 ranges in a test section. The main uncertainty at present is the chemical state of the flow produced by these arc heated low-density wind tunnels. However, at stagnation and enthalpy levels from 4,000 to 9,000 Btu per pound, an arc-heated, low-density wind tunnel was found to produce frozen flow.

84. Peters, R. W., and Wilson, R. C., "Experimental Investigation of the Effect of Convective and Radiative Heat Loads on the Performance of Subliming and Charring Ablators," NASA TN D-1355, July 1962. (*5)
85. Schultz, D. N., and Sweitzer, D. L., "Attitude Control of Space Vehicles Using Minimum Switching Jet Logic," MTP-ASTR-N-62-11, July 1962.

A means to minimize the switching requirements for a jet attitude control system has been investigated. The results are not limited to any specified application, but represent general considerations that can be applied to many types of jet control systems.

The requirements for a jet logic with minimum switching were developed using a single-axis attitude control system. The measured velocity for this system is assumed to be generated by differentiating the sensed displacement; then the velocity and sensed displacement are summed to generate the error signal. This same basic logic was used to develop a three-axis system. Consideration of a control system with limited available electrical power was analyzed with the assumption that only one axis is controlled at any one given time.

Since velocity information is lost when the sensed displacement saturates, a simple velocity sign indicator was used for this study. This indicator provides a velocity threshold to turn the jets off after linear displacement information is lost; it also adds an important factor in the stability of the three-axis system. The results of this study indicate that the number of required switchings can be greatly reduced in a control system using minimum switching logic.

A means to minimize the number of jet firings that occur under the influence of a steady-state disturbance torque was also investigated. This was accomplished by increasing the limit-cycle period length through the use of a pulse storage circuit.

86. Grossman, W., Jr., and Hess, R. V., "Existence of a Voltage Plateau for a Discharge Crossed with a Magnetic Field at Elevated Pressures," paper presented at the Summer Meeting, American Physics Society, Seattle, Washington, August 1962.
87. Roberts, T. G., "The Significance of Spectroscopically Determined Plasma Jet Temperatures," proceedings of the 1962 Army Science Conference, U.S. Military Academy, West Point, New York, Vol. II, 235-250, August 1962.
88. Schaefer, J. W., and Jack, J. R., "Effects of Regenerative and Radiation Cooling on the Performance of Electrothermal Thrusters," NASA TN-D-1738, August 1962.
89. Weltman, R. N., "Design and Calibration of an Arc-Heated Hypersonic, Low-Density Wind Tunnel," NASA TN D-1169, August 1962. (*3)

The design and calibration of an arc heated gas jet that presents a continuous flow in a wind tunnel at Mach numbers of 4 to 5 are described. Uniform flow conditions prevail over a central 1-inch diameter core at static pressures of 0.05 to 0.1 millimeters of mercury with enthalpies up to 4,300 Btu per pound for nitrogen and 1,100 Btu per pound for argon. These conditions correspond to stagnation temperatures up to 9,000° R., to altitudes of about 2,000,000 feet, and to velocities of about 11,000 feet per second.

Details are given for design features that produce stability of a confined arc over long periods of time with arc transfer efficiencies up to 50 percent. For nitrogen, the downstream gas jet is about 5 percent disassociated, and the vibrational energy is in equilibrium before the gas enters the nozzle throat.

Mass-averaged total downstream enthalpies, computed from profile measurements made with total-pressure probes and several stagnation point heat transfer probes of several designs about ¼ inch downstream of the nozzle exit, agree within 10 percent with enthalpies computed from electric power input, mass flow rates, and coolant temperatures rise. The enthalpies determined in the center core are about 20 percent higher.

90. Thom, K., Norwood, J., and Jalufka, N., "Velocity Limitation of a Coaxial Plasma Gun," presented to the International Symposium on Coaxial Plasma Gun, Cleveland, Ohio, September 1962.

Experience with coaxial pulsed plasma guns has shown that the exhaust velocity of such guns usually is one or two orders of magnitude lower than the limiting value E/B of particle drift velocity. This discrepancy has been explained in literature through the "mass loading problem" which describes the technical problem of matching the inertia of the mass of the plasma to the inertia of the electric circuitry which powers the gun. In particular, the "mass loading problem" defines the necessity that the back electromotive force due to the moving plasma, $F_b = Iv(dL/dX)$, quickly exceeds the voltage drop caused by parasitic inductances. Thus, the "mass loading problem" describes essentially terms for determining the efficiency of operation. With no restriction of the energy storage of the driving capacitor bank, the mass-loading problem cannot explain the lag of the observed velocities of the plasma behind the limiting E/B drift velocity. It is found that the friction of the plasma with the walls of the gun is not negligible and that this friction force established a limiting velocity which well agrees with observed exhaust velocities of pulsed plasma guns.

91. Duberg, J. E., "Space Vehicle Environment and Some NASA Facilities for their Simulation," presented at the 31st Symposium on Shock, Vibration, and Associated Environments, Phoenix, Arizona, October 1962.
92. Jack, J. R., "NASA Research on Resistance-Heated Hydrogen Jets," paper presented at Air Force Office Scientific Research (AFOSR) Symposium on Advanced Propulsion Concepts, Cincinnati, Ohio, October 1962.
93. Roberts, T. G., and Hales, W. L., "Radiative Transition Probabilities and Absorption Oscillator Strengths for the Alkali-Like Ions of the Alkaline Earths and for Calcium I," AMC¹ RR-TR-62-8, October 1962. (*9)
94. Stuhlinger, E., "Electric Propulsion 1962—State-of-the-Art Survey," *Astrophysics*, 7, 11, 60-71, November 1962.
95. Stuhlinger, E., and Schwartz, I. R., "The Role of Electric Propulsion in Future Space Programs," paper presented at 17th Annual Meeting of American Rocket Society (ARS), Los Angeles, California, November 1962.
96. Boatwright, W. B., Stewart, R. B., and Grimaud, J. E., "Description and Preliminary Calibration Test of a Small Arc-heated Hypersonic Wind Tunnel," NASA TN D-1377, December 1962. (*5)

A description, modification history, and results of preliminary calibration experiments for a small hypersonic arc-heated wind tunnel are presented. Results obtained with different arc-heater configurations are described, and it is shown that the use of a 12,000 gauss magnetic field to rotate the arc offers distinct advantages over the arc-heater configuration with a 4,000-gauss magnetic field. These advantages are in the form of longer electrode life, less contamination, and increased steadiness of the flow. Although a higher arc voltage resulted for the same gap size for the configuration with the increased magnetic field strength, no increase in arc-heater efficiency was produced. All arc-heater configurations were rather inefficient but this was probably, in part, due to the small throat size used and the correspondingly low air mass flow rates.

Pitot-pressure surveys along the center line at a stagnation pressure of 12 atmospheres and a stagnation temperature of about 3,600°K. showed that the longitudinal Mach number gradient produced in the test section by the 5° half-angle nozzle was shallow. In the 3-inch diameter test section the boundary layer displacement was estimated to be about 0.6 inch.

97. Kennel, H. F., and Schultz, D. N., "A New Concept to Minimize On-Off Jet Fuel Consumption Used for Space Vehicles Attitude Control," MTP-ASTR-N-62-14, December 1962. (*6)

A new concept has been developed to minimize the fuel consumption of a space vehicle attitude control system which uses ON-OFF jet engine thrust for vehicle restoring torque control. The control system is caused to operate with a special type of control logic which was implemented by the use of digital modules. This logic (as a function of certain sensed inputs) causes the vehicle to be placed close to a specific reference attitude with the attitude error rate as small as possible (assuming undisturbed steady-draft rate for a very long time until a specified attitude deadband is reached). After the deadband is exceeded, the remaining portions of the limit cycle must have a finite value of attitude error rate which brings the vehicle back to reference attitude fast and allows the use of large thrust jet engines with correspondingly large minimum impulse. This gives the

¹ Army Missile Command (AMC), Redstone Arsenal, Alabama—Reports available through Technical Library.

attitude control system the capability to compensate the large disturbance torques that are usually used to size the thrust of the attitude control engines. Since long limit cycle periods are obtained, optimum performance with respect to fuel consumption for undisturbed limit cycle operation is achieved. The control system was investigated using three basic types of disturbance torques: impulse disturbance, disturbance as a function of vehicle attitude, and constant disturbance. For a vehicle with a moment-of-inertia ellipsoid of high eccentricity, the dominant steady-state disturbance torque during vehicle orbiting phases is often caused by gravity gradient effects. Therefore, the local vertical must be part of the attitude reference frame for proper utilization of the control logic to minimize jet fuel consumption.

At reference position when the restoring torque is commanded off by the control system, control system tolerance variations can cause the attitude error rate to overshoot beyond zero with the magnitude of the overshoots increasing with time. Because of these tolerance variations, a method for compensation was investigated by adjusting the jet cutoff threshold in flight as a function of a tolerance prediction calculation.

98. Brown, R. D., and Levin, L. R., "A 6-inch Subsonic High Temperatures Arc Tunnel for Structures and Material Tests," NASA L-1356, 1963. (*5)
99. Chapman, A. J., "An Experimental Investigation of Several Ablation Materials in an Electric-Arc-Heated Air Jet," NASA TN D-1520, 1963. (*5)
100. Leonard, W. F., "Measurements of Plasma Temperature and Electron Density Distributions Using Millimeter Waves," paper presented to the Millimeter and Submillimeter Conference IRE, January 1963.
A method for obtaining good solution in the measurement of electron density and temperature variation in a thermal plasma of cylindrical cross section is described. The technique involves the division of a plasma into concentric zones and the evaluation of the attenuation constant in each zone from measured attenuation losses. Results of measurements made on a cyanogen-oxygen flame at 61.2 Gc. are given, and correlation of the peak and average temperature values with spectroscopic and K-band measurements is shown.
101. Jack, J. R., and Spisz, E. W., "Research on Resistance-Heated Hydrogen Jets," paper presented at American Institute of Aeronautics and Astronautics (AIAA) Electric Propulsion Conference, Colorado Springs, Colorado, March 1963.
102. Schaefer, John W., and Ferrante, John, "Analytic Evaluation of Possible Noncryogenic Propellants for Electrothermal Thrustors," NASA TN D-2253. (*3)
103. Jack, John R., and Schaefer, John W., "Possible Effects of Non-uniform Flows on the Performance of Electrothermal Thrustors," NASA TN D-1732. (*3)
104. Shepard, Charles E., and Watson, Velvin R., "Performance of a Constricted-Arc Discharge in a Supersonic Nozzle," Paper No. 63-380 Fifth Biennial Gas Dynamics Symposium, Northwestern University Technological Institute, Evanston, Illinois, August 14-16, 1963. (*4)
105. Technical Documentary Report No. ASD-TDR-62-729, AF Materials Lab., ASD AFSC Wright-Patterson AFB, Ohio. Prepared under contract No. AF 33(616)7578 by the AVCO Corp., Research and Advanced Development Division, Wilmington, Mass., September 1963.

106. Stine, Howard A., "The Hyperthermal Supersonic Aerodynamic Tunnel," presented at International Symposium on High Temperature Technology, Asilomar, California, September 8-11, 1963. (*4)
107. Shepard, Charles E., Watson, Velvin R., and Stin, Howard A., "Evaluation of a Constricted-Arc Supersonic Jet," NASA TN D-2066, 1964. (*4)
108. Winovich, Warren, "On the Equilibrium Sonic-Flow Method for Evaluating Electric-Arc Air-Heater Performance," NASA TN D-2132, 1964. (*4)
109. Jack, John R., Spisz, E. W., and Brinich, P. F., "Research on Resistance Heated Hydrogen Thrustors," NASA TN D-2281. (*3)
110. Hiester, Nevin K., and Clark, C. F., "Relative Operating Capabilities of Selected Electric-Arc Reentry Environment Simulators," Stanford Research Institute, Technical Report No. 1, May 1964.
111. Jedlicka, James R., "Shape of a Magnetically Rotated Arc in an Annular Gap," R-1981, Proposed NASA TN.
112. Stine, Howard A., "Arc Heaters and MHD Accelerators for Aerodynamic Purposes," R-2398, AGARD Paper.
113. Stine, Howard A., "Advances in Arc-Jet Technology," R-2318, AEC-NASA Conference.
114. Shepard, Charles E., Watson, Velvin R., and Stine, Howard A., "Performance of the Supersonic-Arc Plasma Jet," Proposed TN.
115. Ducati, A. C., Giannini, Gabriel M., and Muehlberger, Eric, "High Specific Impulse Thermo-Ionic Acceleration," AIAA Paper 64-668, AIAA 4th Electric Propulsion Conference, Philadelphia, Pennsylvania, August 31, 1964.
116. John, Richard R., Bennett, Stewart, and Connors, John F., "Experimental Performance of a High Specific Impulse Arc Jet Engine," AIAA Paper 64-669, AIAA 4th Electric Propulsion Conference, Philadelphia, Pennsylvania, August 31, 1964.
117. Todd, James P., and Sheets, Ronald E., "The Development of a Regeneratively-Cooled 30-kw. Arc Jet Engine," AIAA Paper 64-671, AIAA 4th Electric Propulsion Conference, Philadelphia, Pennsylvania, August 31, 1964.
118. John, R. R., Debolt, A., Hermann, M., Hogan, W., Kusko, A., and Liebermann, R., "Theoretical and Experimental Investigation of Arc Plasma-Generation Technology," AIAA 4th Electric Propulsion Conference, Philadelphia, Pennsylvania, August 31-September 1, 1964.

Part I: "Applied Research on Direct and Alternating Current Electric Arc Plasma Generators"

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119. Carter, A. F., et al., "Research on a One-Inch-Square Linear d.c. Plasma Accelerator," presented at the AIAA Fourth Electric Propulsion Conference, August 1964.
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121. Wood, G. P., et al., "Research on Linear Crossed-Field Steady-Flow d.c. Accelerators at Langley Research Center NASA," presented at the AGARD Specialists' Meeting on "Arc Heaters and MHD Accelerators for Aerodynamic Purposes," September 1964.
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209. NAS 8-895, Oswalt, L. R., Koppang, R. R., Harp, J. L., Jr., Koffer, G. W., Sherwood, C. M., and Krull, H. G., "Investigation of Exhaust Nozzle Flow Phenomena in Arc-Jet Engines," ASTRO-The Marquardt Corp., March 1961 to April 1962. (Transferred to Lewis Research Center March 1962.)
210. NAS 8-1527, Ambrosini, D. E., Page, R. J., and Humpal, H., "Study of Flight Test Objectives for Electrothermal Propulsion System," Plasmadyne Corp., February 1961 to August 1961.
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218. NAS 8-2515, Richter, R., and Martinek, F., "Study of A. C. Arc Dynamics Stabilization and Starting Criteria," General Electric Co., June 1961 to December 1962. (Transferred to Lewis Research Center, December 1961, follow-on NAS 3-2523.)
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